

Frontier Physics at a High Intensity Proton Facility

Leptonic Flavor Violation and Much More

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Outline

1. Future FNAL Fixed Target Physics (Comments)
 \bar{p} , charm, hyperons, kaons, neutrinos, muons...
2. Rare Kaon Decays ($K \rightarrow \pi \nu \bar{\nu} \dots$) Golden Modes
3. Neutrino Scattering (NuSOnG LOI)
- *4. Muon Physics
 - i) Muon Anomalous Magnetic Moment (3.4σ dev.)
 - ii) Coherent Muon-Electron Conversion (mu2e LOI)
- *5. Neutrino Oscillations (FNAL-Homestake 1300km)
Very Large Detector (300kton H₂O or 100kton LArgon...)
Leptonic CP Violation, θ_{13} , Mass Hierarchy,...Precision
Proton Decay, Supernova ν , Atmospheric ν ,...
6. Concluding Remarks

1. Future FNAL Fixed Target Physics

- Currently: Booster(8GeV), Main Injector(30-120GeV), Tevatron(800+GeV) & 2TeV $p\bar{p}$ Collider +Accumulator, Debuncher, Recycler ...
- SNuMi: MI (0.4MW at 50GeV, 1.2MW at 120GeV)
- Project X: 8GeV Linac (1% of ILC) R&D Project?
MI (2MW 50-120GeV)!
Better Proton Economics

- Broad Fixed Target Program: \bar{p} , charm, hyperons, kaons, neutrinos, muons...
- LOIs submitted, Proposals being prepared
Standard Model & Beyond
- Is the program big (exciting) enough for FNAL?, USA?
What Cost? Interest? Competition?
- I will consider a few examples: (K, μ , ν & DUSEL-FNAL (shotgun) Marriage)

2. Rare Kaon Decays

- $K \rightarrow \pi \nu \bar{\nu}$: (SM Tests & New Physics Probes)

SM Predictions: $\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) \approx 7.8(8) \times 10^{-11}$

$$\text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu}) \approx 2.5(4) \times 10^{-11}$$

BNL E787&949: $\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 1.47(1.3/0.89) \times 10^{-10}$
(3 events)

Future Goals: $\pm 10\%$ measurements (≥ 100 events)

Comparison with B decays tests New Physics $\sim 3000\text{TeV}!$

Needs Project X (Very Good Motivation)

Other: $K_L \rightarrow \pi^0 e^+ e^-$, $e^+ e^-$, $e^+ \mu^-$; $K^+ \rightarrow \pi \nu \mu(\text{pol})$, $e^+ \nu \dots$

One Loop Contributions to $K \rightarrow \pi \nu \bar{\nu}$ (E949)

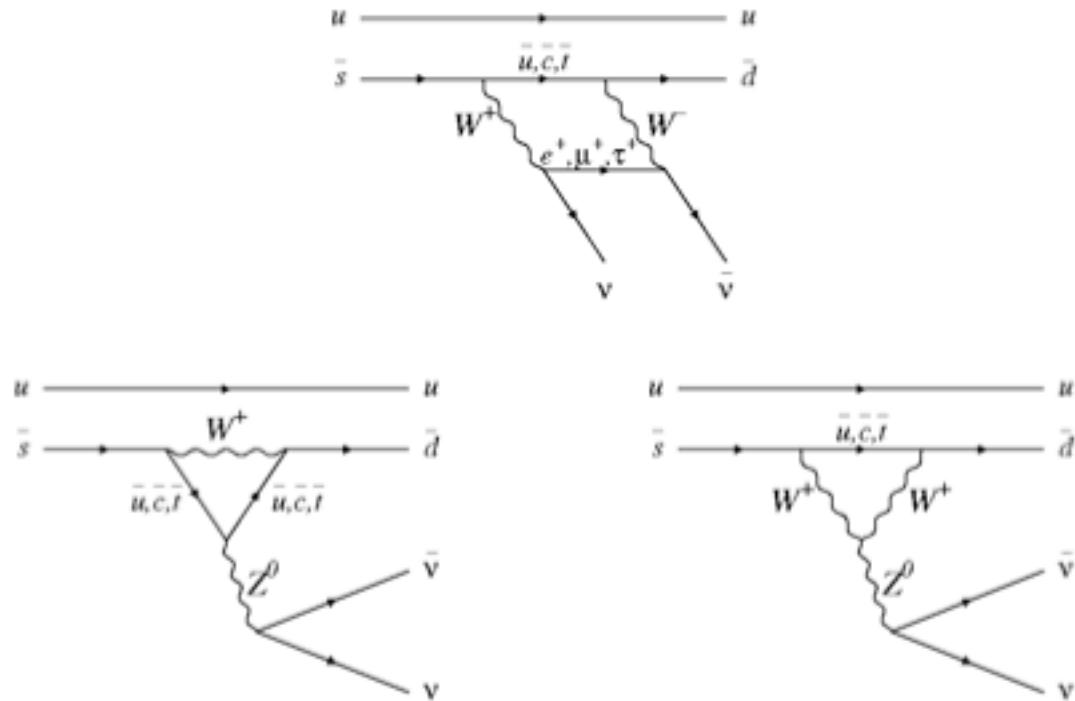
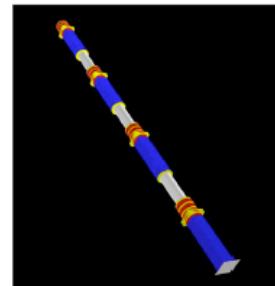


FIG. 3: Second-order weak processes that contribute to the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ branching ratio: the “Box” diagram (upper) and two “Z-penguin” diagrams (bottom).

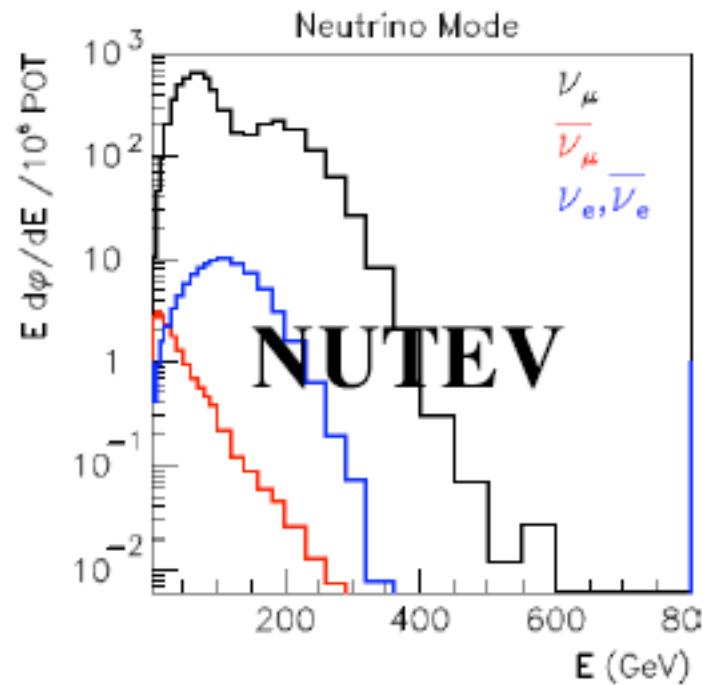
3. Neutrino Scattering

NuSOnG:
Neutrino Scattering on Glass



Janet Conrad, Peter Fisher
Autumn 2007 PAC Meeting
Nov 2, 2007

A high-statistics, high energy neutrino experiment...



High energy,
very pure beam
($\times 20$ POT)

+



CHARM II

Fine-grained,
massive detector
($\times 6$ mass)

We are in the process of exploring the best run-plan
Physics in this talk assumes 1.5E20 POT in ν , 0.5E20 POT in $\bar{\nu}$

Broad Physics Program: Structure Functions, Exotica,...

Redo NuTeV with $\sim 1/2$ $\sin^2\theta_W$ error in DIS νq scattering

(NuTeV $\sin^2\theta_W(m_Z)_{\overline{\text{MS}}} = 0.2361(17)$ 3 sigma too high)

$$\sigma(\nu_\mu e \rightarrow \nu_\mu e) / \sigma(\nu_\mu e \rightarrow \mu \nu_e) \rightarrow \Delta \sin^2\theta_W \approx \pm 0.0016$$

Together with: APV(e^-Cs), Moller (e^-e^-), $Q_W(ep)$

And compared with Z pole $\sin^2\theta_W(m_Z)_{\overline{\text{MS}}} = 0.2312(2)?$

Constrains New Physics at 1-2 TeV (Z' , Extra Dim...)

$$\Delta S \& \Delta T \sim \pm 0.1-0.2$$

Complements LHC Discoveries

Other Experiments Needed for Tevatron Program

4. Muon Physics

i) Muon Anomalous Magnetic Monent

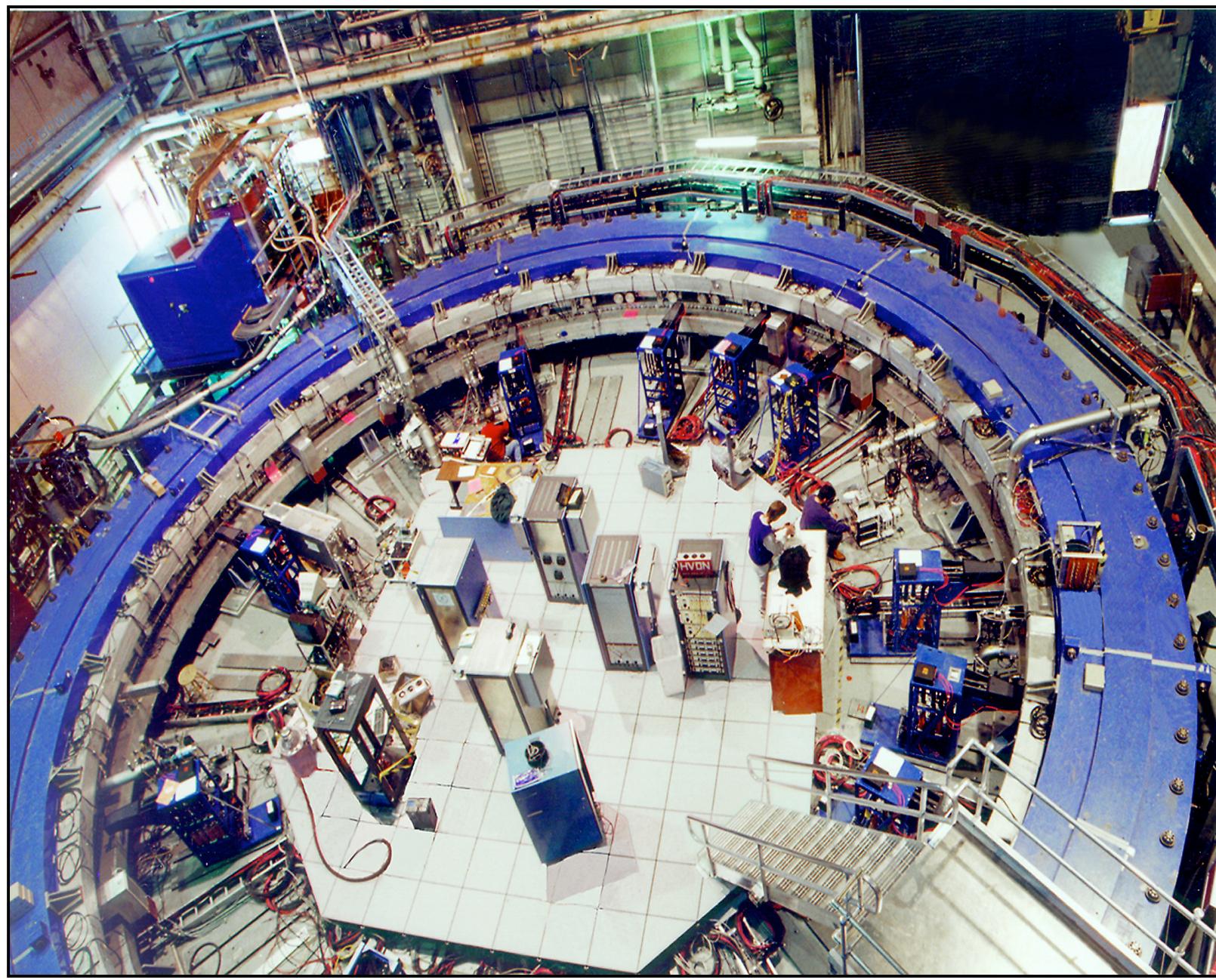
Experimental Result: E821 at BNL

$$a_{\mu}^{\text{exp}} \equiv (g_{\mu} - 2)/2 = 116592080(54)_{\text{stat}}(33)_{\text{sys}} \times 10^{-11}$$
$$= 116592080(63) \times 10^{-11}$$

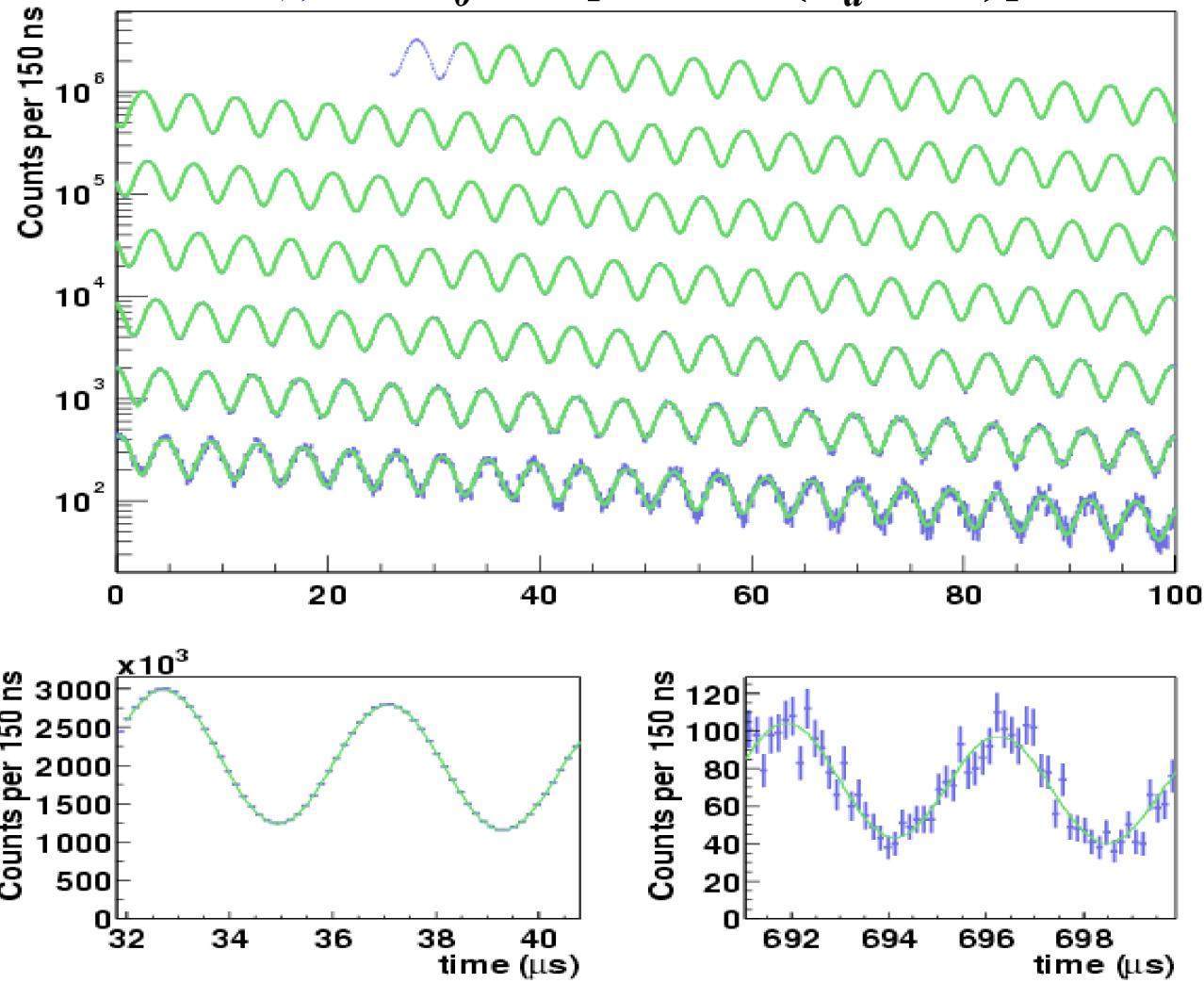
Factor of 14 improvement over CERN results
(3.4 sigma deviation from theory!)

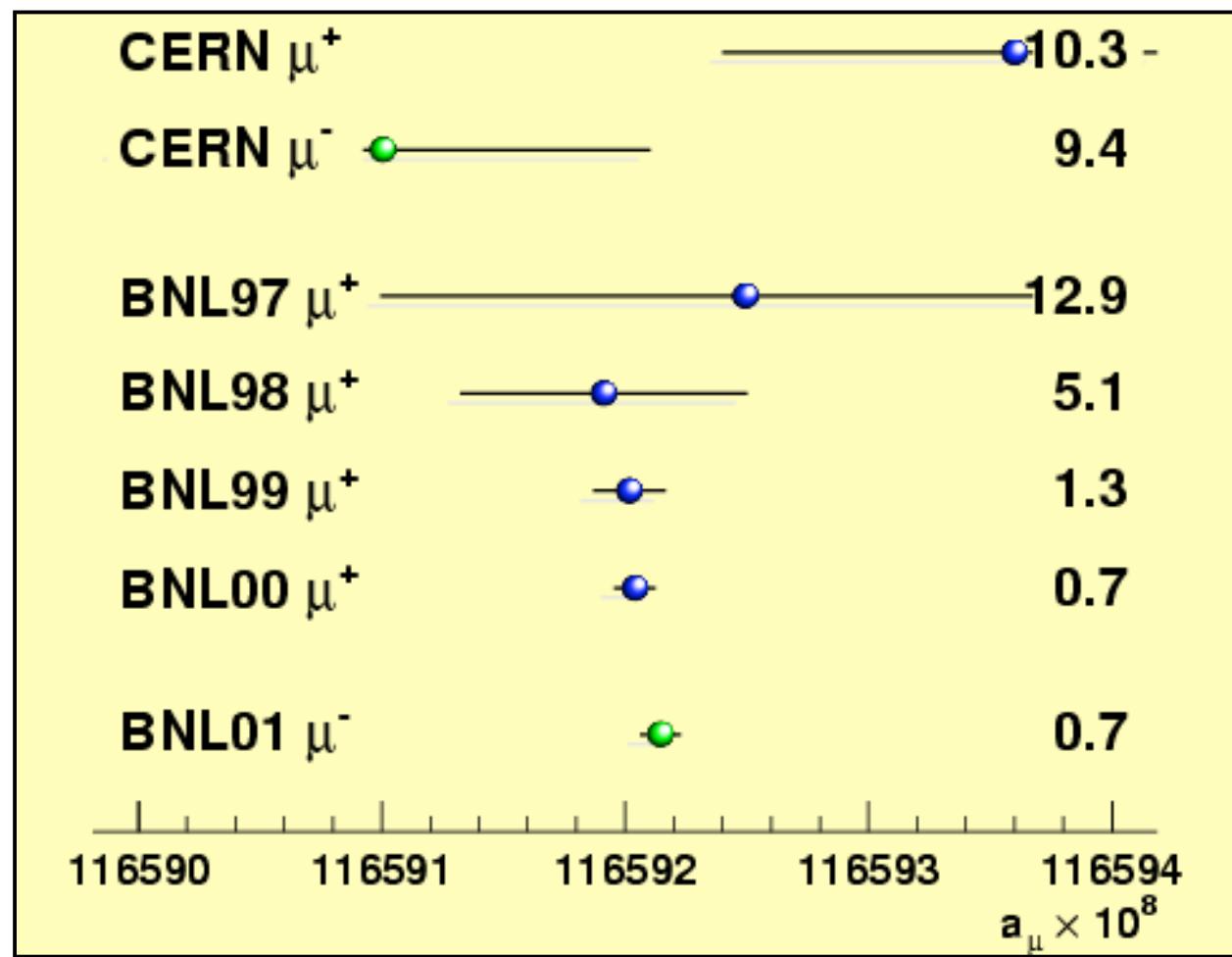
Crack in the Standard Model?

- E969 Goal: Further Factor ~2 Improvement
Examining Possible Factor 5 Upgrade!(Legacy Run)
And Perhaps Move To Fermilab! (Muon Economics)



$$N(t) = N_0 e^{-t/\tau} [1 + A \cos(\omega_a t + f)]$$





Standard Model Prediction

$$a_{\mu}^{\text{SM}} = a_{\mu}^{\text{QED}} + a_{\mu}^{\text{EW}} + a_{\mu}^{\text{Hadronic}}$$

- QED Contributions:

- $a_{\mu}^{\text{QED}} = 0.5(\alpha/\pi) + 0.765857410(27)(\alpha/\pi)^2 + 24.05050964(87)(\alpha/\pi)^3 + \underline{130.8055(80)}(\alpha/\pi)^4 + 663(20)(\alpha/\pi)^5 + \dots$ (5 loops!)

$$\alpha^{-1} = 137.035999070(98) \quad \text{From } a_e \text{ (new)}$$

$$a_{\mu}^{\text{QED}} = \underline{116584718.1(2) \times 10^{-11}} \quad \text{Very Precise!}$$

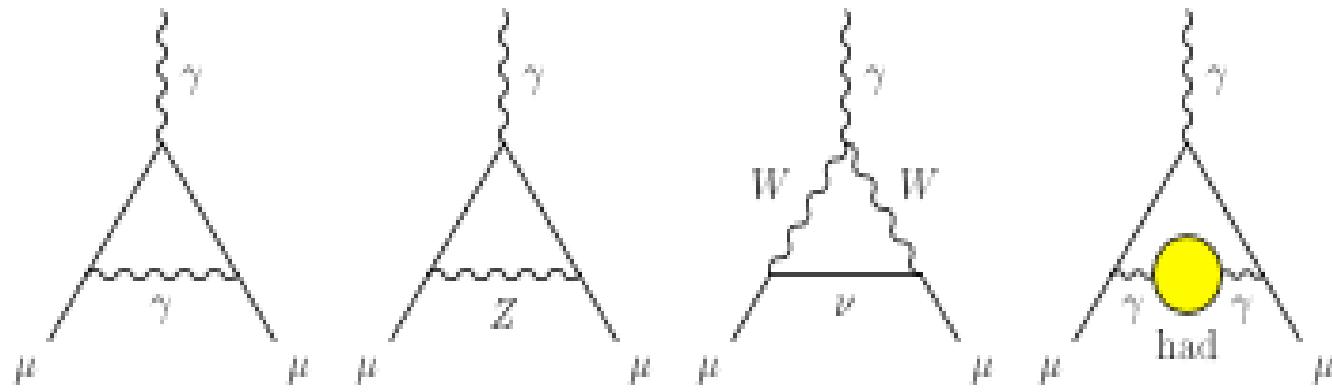


Figure 1: Representative diagrams contributing to a_μ^{SM} . From left to right: first order QED (Schwinger term), lowest-order weak, lowest-order hadronic.

Electroweak Loop Effects

$$a_{\mu}^{\text{EW}}(\text{1 loop}) = \underline{194.8 \times 10^{-11}}$$
 goal of E821

2 loop EW corrections are large -21%

$$a_{\mu}^{\text{EW}}(\text{2 loop}) = \underline{-40.7(1.0)(1.8) \times 10^{-11}}$$

3 loop EW leading logs very small $O(10^{-12})$

- $a_{\mu}^{\text{EW}} = \underline{154(2) \times 10^{-11}}$ Non Controversial

EW Uncertainty $\sim \pm 2 \times 10^{-11}$

Negligible

From $e^+e^- \rightarrow$ hadrons data + dispersion relation

$$a_\mu^{\text{Had}}(\text{V.P.})^{\text{LO}} = \underline{6894(42)(18)} \times 10^{-11} \text{ (Hagiwara et al)}$$

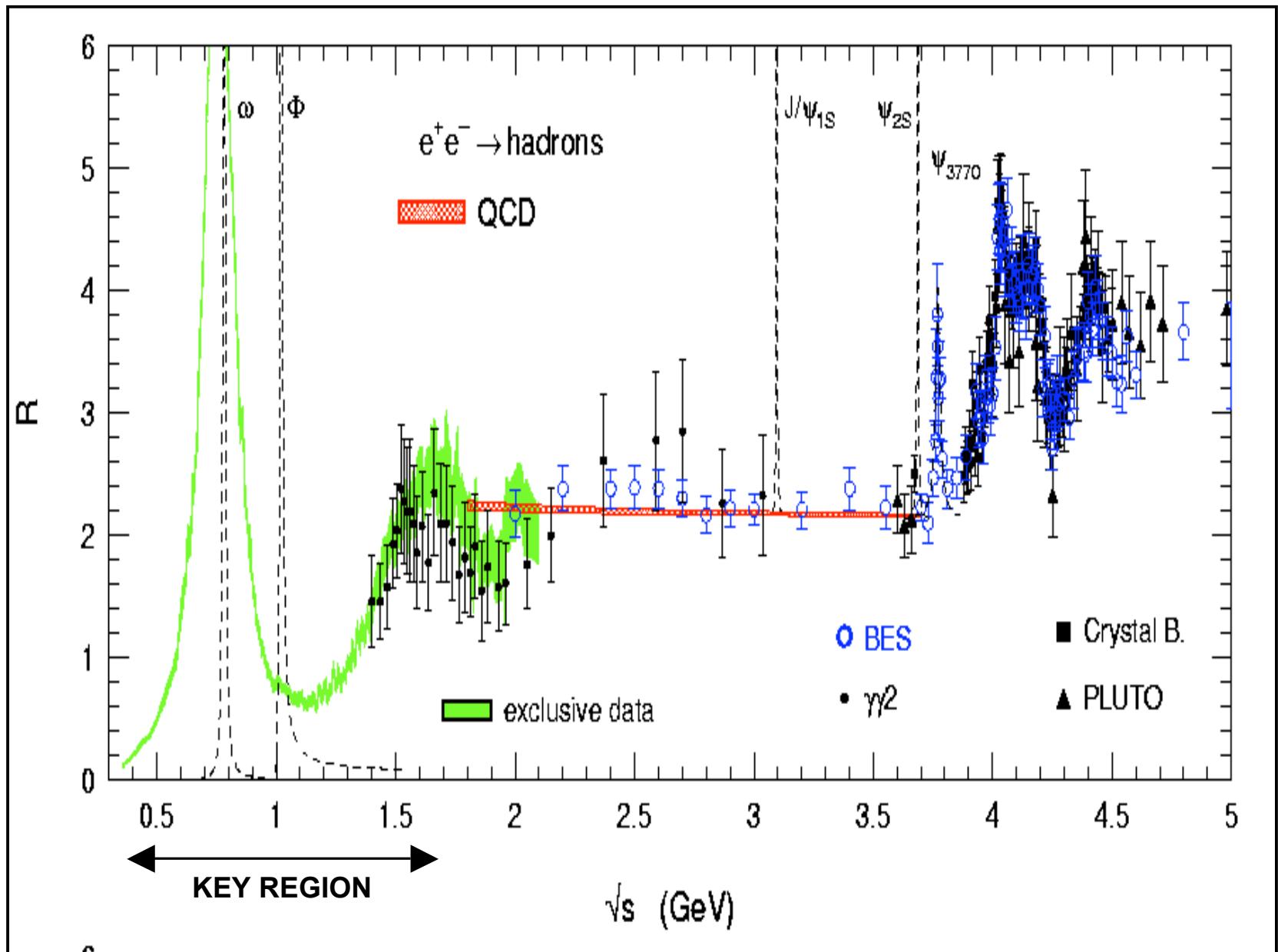
$$\underline{3 \text{ loop}} = a_\mu^{\text{Had}}(\text{V.P.})^{\text{NLO}} + a_\mu^{\text{Had}}(\text{LBL})$$

$$a_\mu^{\text{Had}}(\text{V.P.})^{\text{NLO}} = -98(1) \times 10^{-11}$$

$$a_\mu^{\text{Had}}(\text{LBL}) = 120(35) \times 10^{-11}$$

$$a_\mu^{\text{Had}} = \underline{6916(42)(18)(35)} \times 10^{-11}$$

$$a_\mu^{\text{SM}} = \underline{116591788(2)(46)(35)} \times 10^{-11}$$



$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 292(63)_{\text{exp}}(58)_{\text{th}} \times 10^{-11} \text{ (3.4}\sigma\text{!)}$$

- New Physics? Nearly 2xStandard Model EW!
Most Natural Explanation: SUSY Loops

Generic 1 loop SUSY Contribution:

$$a_\mu^{\text{SUSY}} = (\text{sgn}\mu) 130 \times 10^{-11} (100 \text{GeV}/m_{\text{susy}})^2 \tan\beta$$

$\tan\beta \approx 3-40$, $m_{\text{susy}} \approx 100-500 \text{GeV}$ Natural Explanation Range

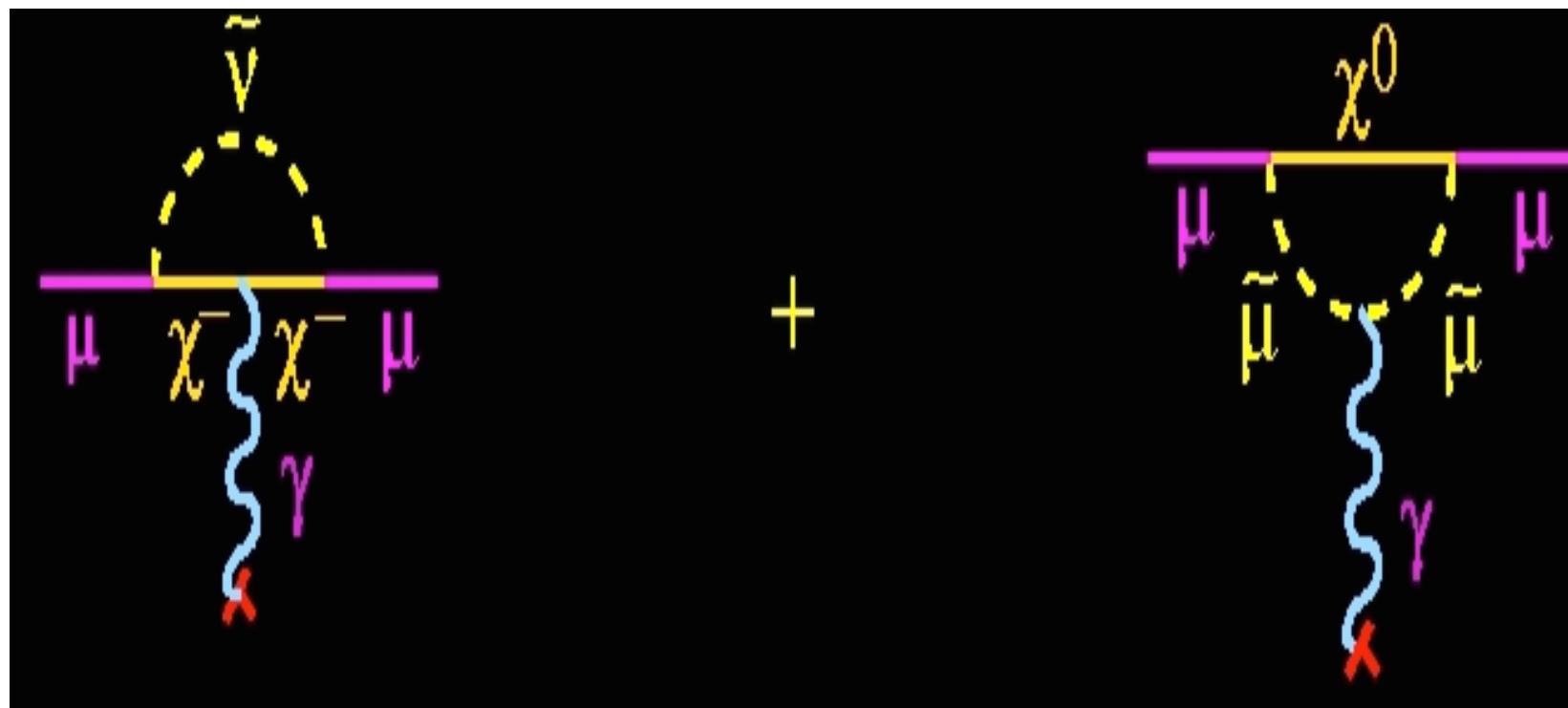
Other Explanations: Hadronic? $\tau \rightarrow \pi^- \pi^0 \nu_\tau$ +isospin data

$$(\Delta a_\mu = 83(92) \times 10^{-11} \text{ agreement!})$$

Other New Physics $\sim 2 \text{TeV}$

Experiment? (must redo)

SUSY 1 loop a_μ Corrections



- Slepton mixing → Lepton Flavor Violation!
Suppression due to near degeneracies in loops
Nevertheless, we should expect: edms, $\mu \rightarrow e\gamma$,
 $\mu^+ \rightarrow e^+ e^- e^+$, $\mu N \rightarrow e N$, $\tau \rightarrow \mu\gamma$, $\tau \rightarrow \mu\mu\mu$, ...
 $g_\mu - 2$ deviation strengthens case for searches!
MEG at PSI will do:
 $\text{BR}(\mu \rightarrow e\gamma) \leq 1.2 \times 10^{-11} \rightarrow 2 \times 10^{-13}$ SES
(Factor ~ 25 improvement)

ii) μ 2e at Fermilab(LOI): $R(\mu\text{Al} \rightarrow e\text{Al}) \rightarrow 2 \times 10^{-17}!$

- Coherent μ -e Conversion in Nuclei ($\mu\text{N} \rightarrow e\text{N}$)

Stop μ^- in material, $\sim 10^{-10}$ sec, μ^-N (1S) atom forms

$$\text{i) } \Gamma(\mu^- \rightarrow e^- \bar{\nu} \bar{\nu}) = 0.5 \times 10^6/\text{sec}$$

$$\begin{aligned} \text{ii) } \omega(\mu^-N \rightarrow \nu_\mu N') &= 0.7 \times 10^6/\text{sec} \quad (\text{N=Al}) \\ &= 2.6 \times 10^6/\text{sec} \quad (\text{N=Ti}) \end{aligned}$$

$$\text{iii) } \mu^-N \rightarrow e^-N \quad \omega(\mu^-Ti \rightarrow e^-Ti) < 7 \times 10^{-13} \omega(\mu^-Ti \rightarrow \nu_\mu) \text{ (Prelim.)}$$

*Signature: m_μ -BE=105 MeV monoenergetic electron
single particle \rightarrow no accidentals \rightarrow high rate capability!

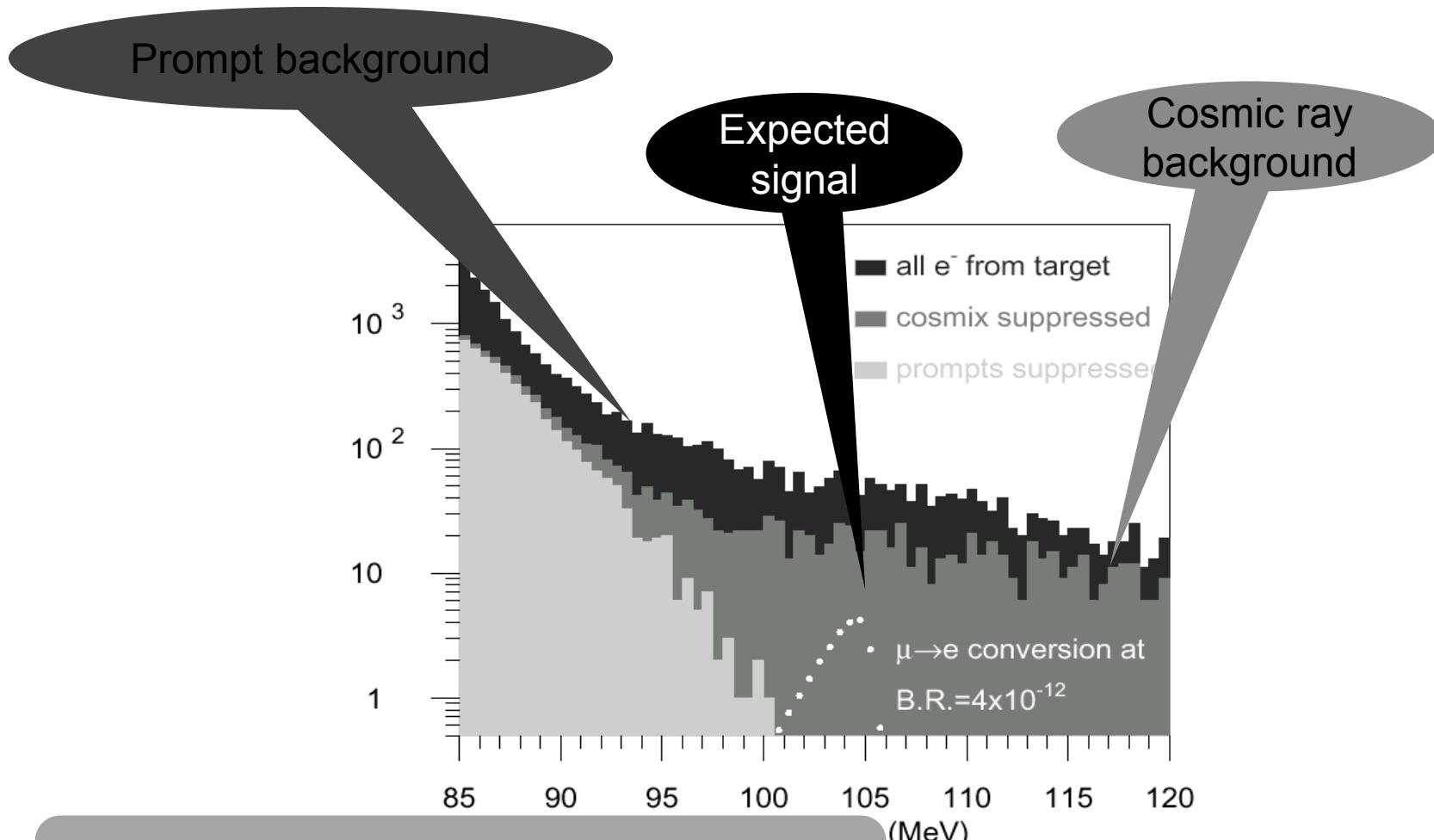
It can take every muon we can provide!

MECO at BNL would have stopped $10^{11} \mu^-/\text{sec}$!

wait $\sim 0.6 \times 10^{-6}$ sec (reject prompt background)

Requires ~ 300 keV resolution & Clean beam between pulses

potential sources of fake backgrounds specify much of the design of the beam and experimental apparatus.



Experimental signature is 105 MeV e^- originating in a thin stopping target.

Charged Lepton Number Violating Processes

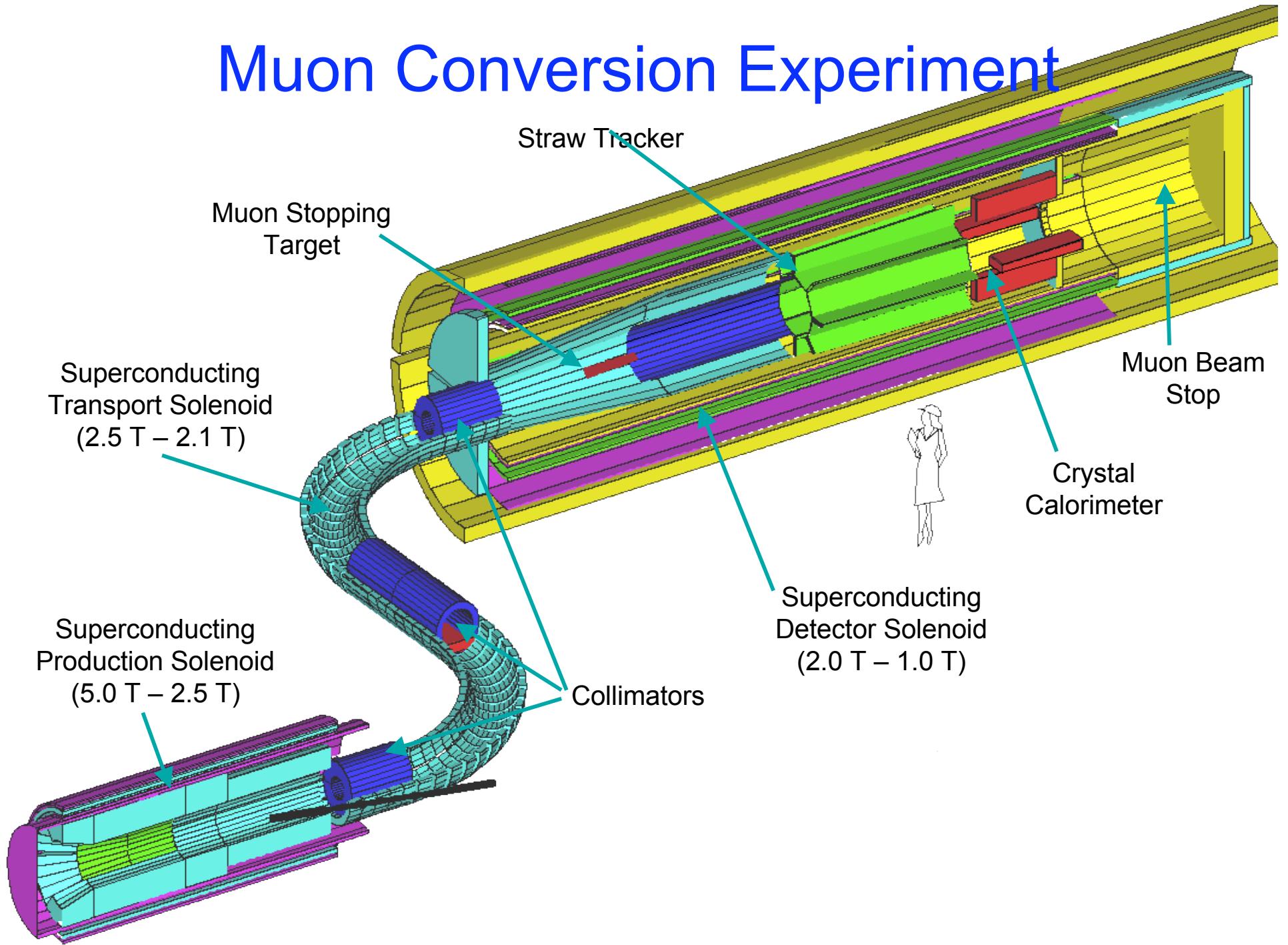
Reaction	Bound	In Progress	Proposed	Possible
$\text{BR}(\mu \rightarrow e\gamma)$	$<1.2 \times 10^{-11}$	$2 \times 10^{-13} \text{ SES}$	$2 \times 10^{-14} \text{ SES}$?
$\text{BR}(\mu \rightarrow eee)$	$<1 \times 10^{-12}$	-		10^{-14}
$R(\mu Ti \rightarrow e Ti)$	$<4 \times 10^{-12}$ $<(7 \times 10^{-13})$	-	$2 \times 10^{-17} \text{ SES}$	10^{-19}
	$R(\mu Ti \rightarrow e Ti) \text{ at } 7 \times 10^{-13} \sim R(\mu Al \rightarrow e Al) \text{ at } 4 \times 10^{-13}$			
$\text{BR}(\mu \rightarrow e\gamma\gamma)$	$<7.2 \times 10^{-11}$	-		
$\text{BR}(K_L \rightarrow \mu e)$	$<4.7 \times 10^{-12}$			10^{-13}
$\text{BR}(\tau \rightarrow \mu\gamma)$	$<6.8 \times 10^{-8}$			10^{-9}
$\text{BR}(Z \rightarrow \mu e)$	$<1.7 \times 10^{-6}$	(10 ⁻¹³ from $\mu Ti \rightarrow e Ti$!)		

- The key to reaching 2×10^{-17} SES in $\mu 2e$ is to copiously produce and stop $10^{11} \mu^-/s$ using an intense 8GeV proton beam on target in a trapping solenoid.

The proton beam must be clean to 1 part in 10^9 - 10^{10} between pulses.

Possible at Fermilab using 8GeV Infrastructure!
(Must Do Experiment!)

Muon Conversion Experiment



Some Theory Considerations:

If transition dipole operator (chiral changing) dominates

$$BR(\mu \rightarrow e\gamma) = 389 R(\mu Al \rightarrow eAl) = 238 R(\mu Ti \rightarrow eTi)$$

But conversion exp. can be more sensitive by 10^3 - 10^4 !

Eg. Popular SUSY Models (may be related to Δa_μ)

Neutrino Mass & Mixing Effects → Lepton Flavor Violation

$$BR(\mu \rightarrow e\gamma) \sim 3\alpha/32\pi [m_3^2 - m_2^2]^2 / m_W^4 (s_{13}c_{13}s_{23})^2 \leq 10^{-54}$$

$R(\mu N \rightarrow eN) \sim 100 BR(\mu \rightarrow e\gamma) \sim 10^{-52}$ still tiny, but enhanced by Chiral conserving amplitudes.

(Lesson) Conversion better for Heavy Neutrino Mixing

In General: $1/200 < BR(\mu \rightarrow e\gamma) / R(\mu N \rightarrow eN) < 200$

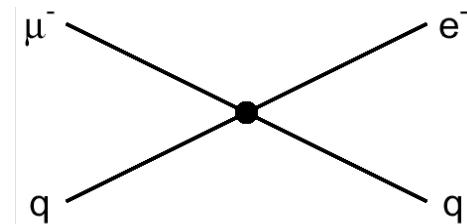
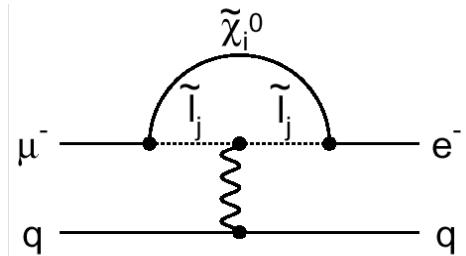
Conversion More Robust! Better Discovery Potential

If MEG ($\mu \rightarrow e\gamma$) at PSI sees ~ 5 events,

$\mu 2e$ should see 100-20,000 events!

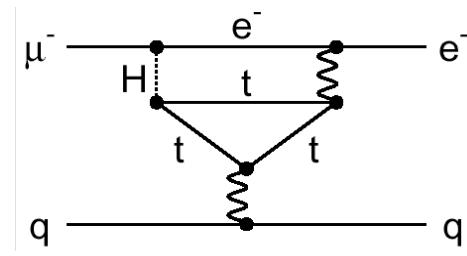
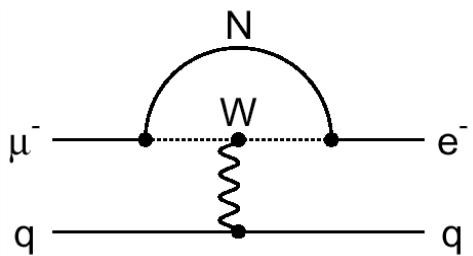
Sensitivity to Different Muon Conversion Mechanisms

Supersymmetry
Predictions at 10^{-15}



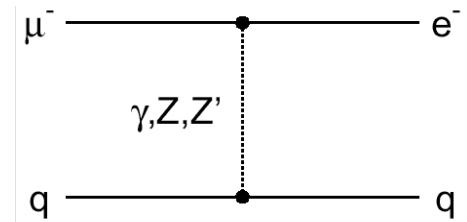
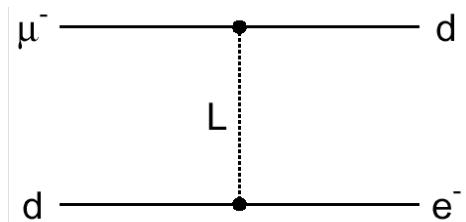
Compositeness
 $E_c = 3000 \text{ TeV}$

Heavy Neutrinos



Second Higgs
doublet

Leptoquarks



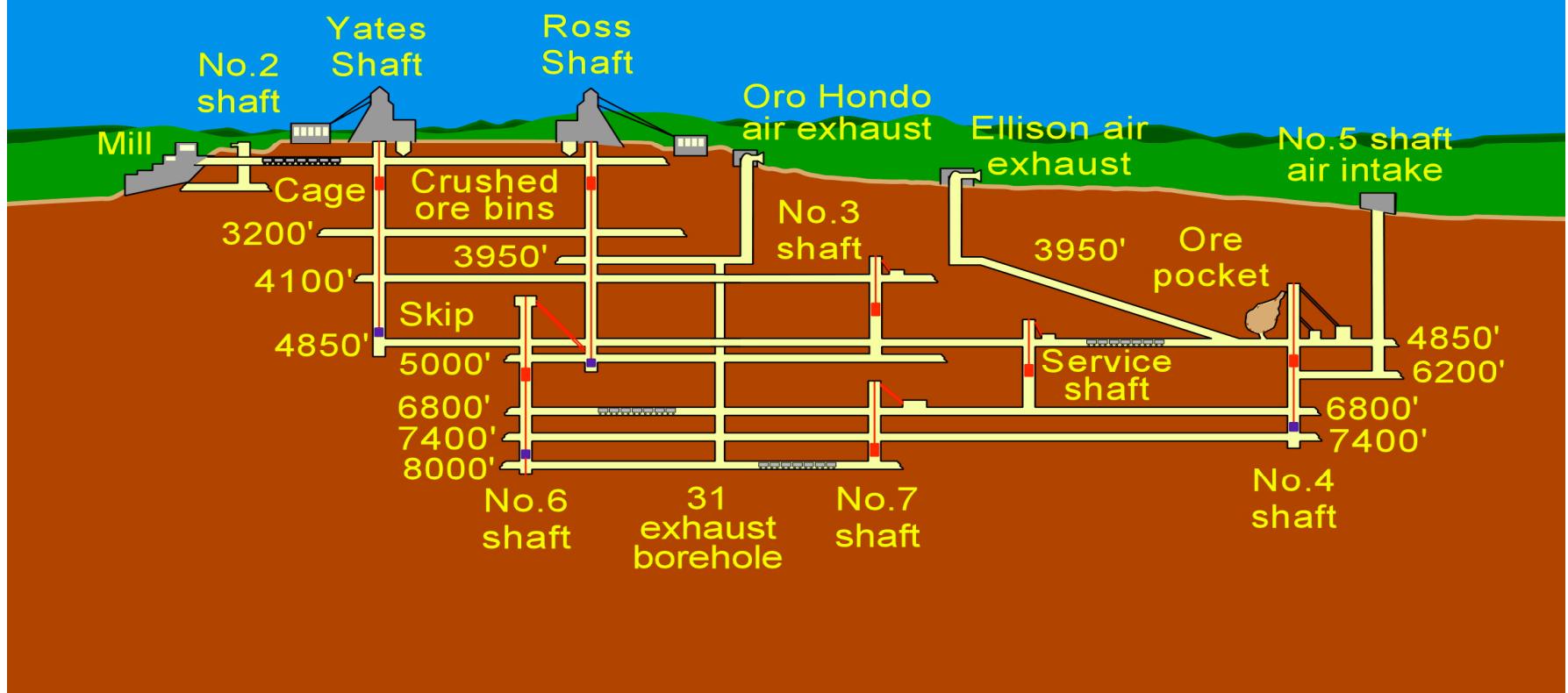
Heavy Z' ,
Anomalous Z
coupling

5. Neutrino Oscillations (FNAL-DUSEL 1300km)

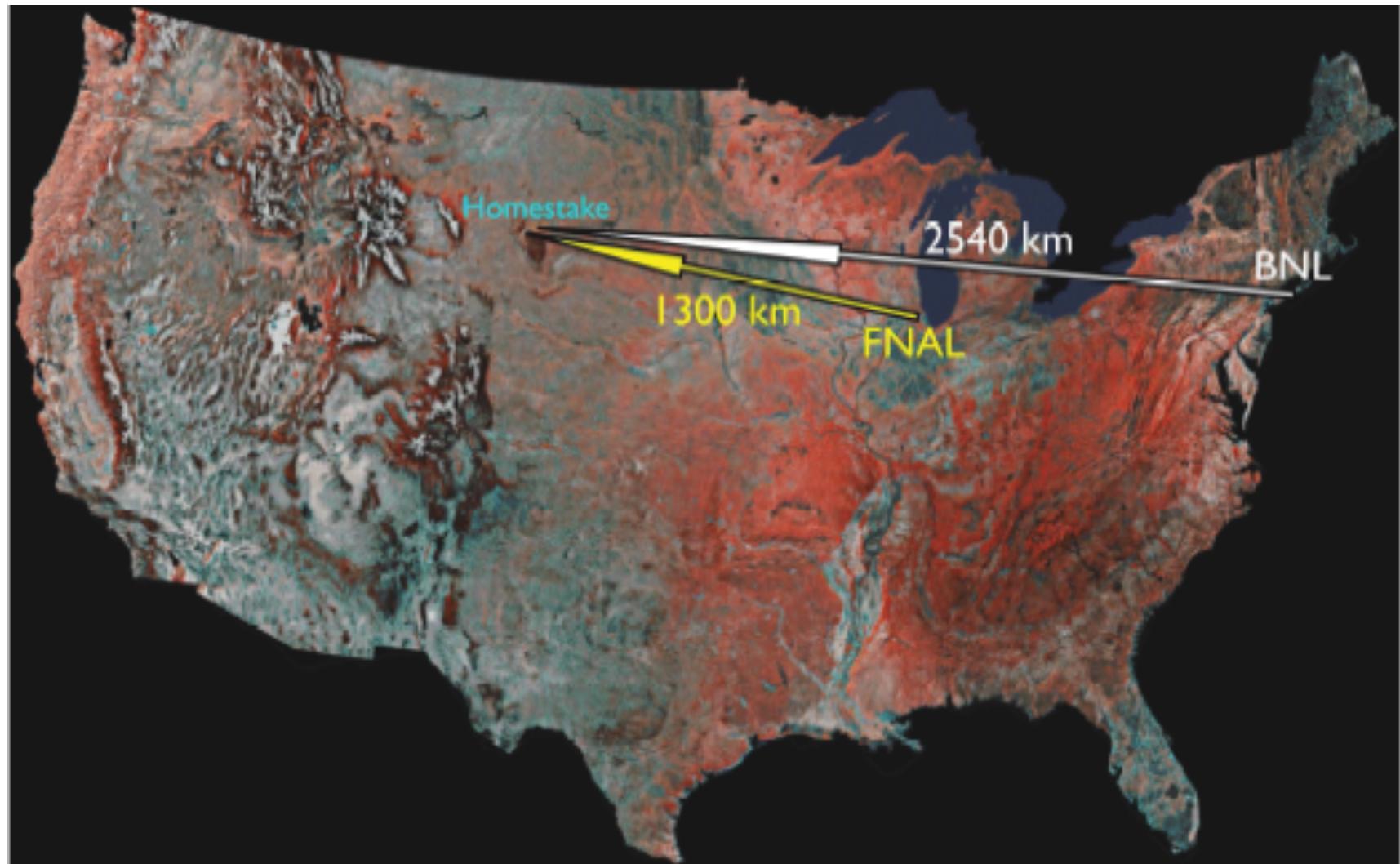
- What (and where) is DUSEL?
- Homestake Gold Mine in South Dakota Chosen As Site For NSF Deep Underground Science And Engineering Lab (DUSEL). Expects \$400-500M Funding. \$200M for Lab and \$200M for (first round) experiments.
- Currently \$5M/yr for 3 yr to develop proposal.
- Thanks to a generous benefactor Mr. Sanford (\$70M)
DUSEL \Rightarrow SUSEL
- Already has one Nobel Prize: Ray Davis Solar Neutrinos
- Expects to have neutrino oscillation program!



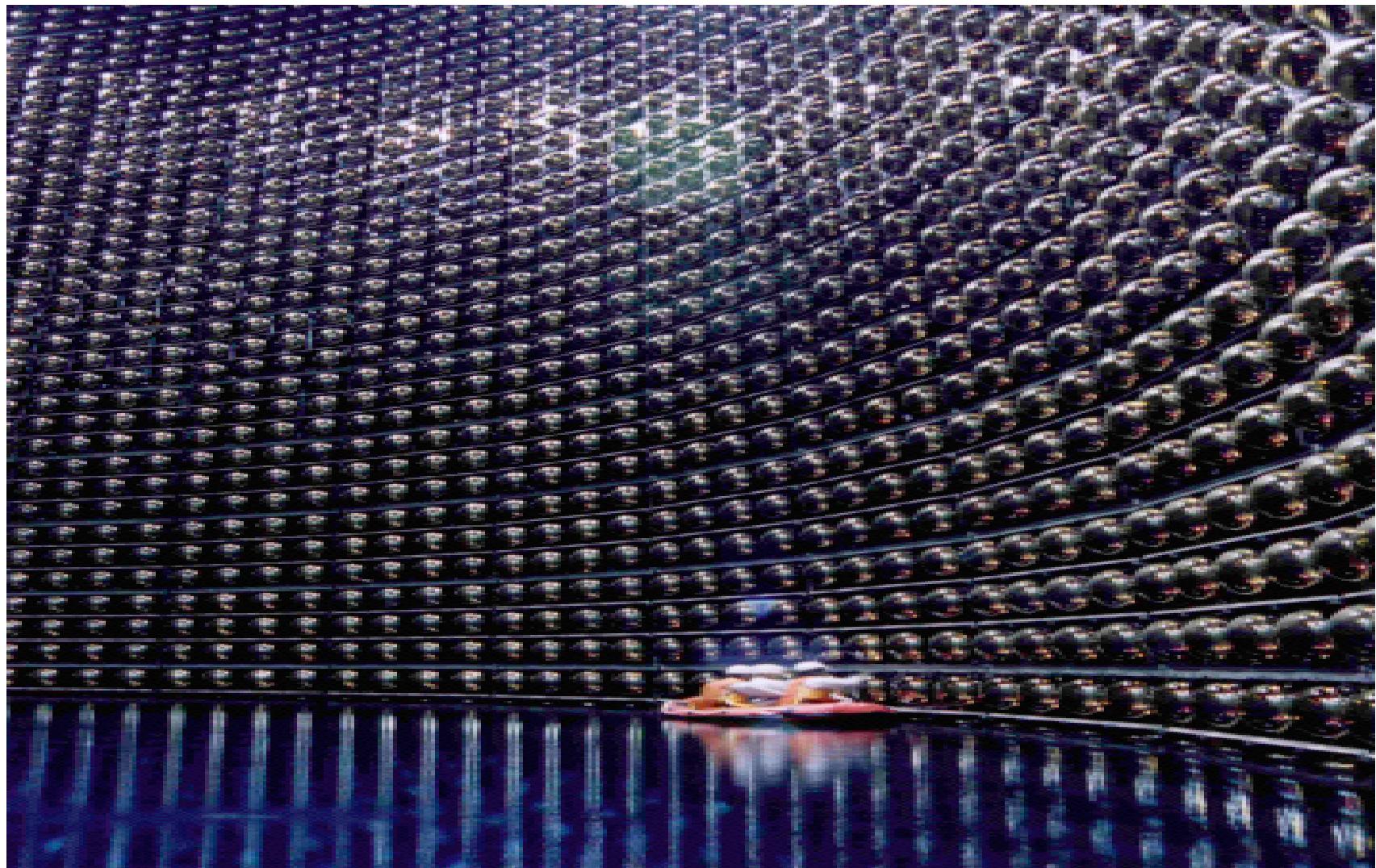
General Homestake Mine Development



Very Long Baseline Neutrino Oscillations (Fermilab or BNL- Homestake)



SUPER KAMIOKANDE



Neutrino Masses and Mixing (formalism & status)

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = U \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix} \quad (1)$$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$c_{ij} = \cos \theta_{ij}, \quad s_{ij} = \sin \theta_{ij}$$

$$J_{CP} \equiv \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos \theta_{13} \sin \delta. \quad (2)$$

Current Neutrino Mixing Parameters

- $\Delta m_{32}^2 = m_3^2 - m_2^2 = \pm 2.7(3) \times 10^{-3} \text{ eV}^2$
- $\Delta m_{21}^2 = m_2^2 - m_1^2 = +7.6(2) \times 10^{-5} \text{ eV}^2$

(Recent very precise KamLAND Measurement)

$\Delta m_{21}^2 / \Delta m_{32}^2 \approx 1/35 \rightarrow$ CP Violation Exp Doable!

Hierarchy $m_3 > m_1$ (normal) or $m_3 < m_1$ (inverted)?

$\theta_{23} \sim 45^\circ \quad \sin^2 2\theta_{23} = 1.0 \quad (\theta_{23} \text{ or } 90^\circ - \theta_{23})$

$\theta_{12} \sim 34^\circ \quad \sin^2 2\theta_{12} = 0.86$

$\theta_{13} \leq 11^\circ \quad \sin^2 2\theta_{13} \leq 0.15$ (How Small?)

$0 \leq \delta \leq 360^\circ ?$

$J_{CP} \approx 0.11 \sin 2\theta_{13} \sin \delta$ (potentially very large)

($J_{CP}(\text{quarks}) \approx 3 \times 10^{-5}$)

What do we still need to learn?

- 1. Value of θ_{13} ? (Daya Bay Reactor $\sin^2 2\theta_{13} \rightarrow 0.01$)
- 2. Sgn Δm_{32}^2 ? (Important for Neutrinoless $\beta\beta$ Decay)
- 3. Value of δ ?, J_{CP} ?, CP Violation? ([Holy Grail](#))
- 4. Precision Δm_{32}^2 , Δm_{21}^2 , θ_{23} , θ_{12}
- 5. Absolute Mass (Tritium β decay, Neutrinoless $\beta\beta$)
- 6. “New Physics” - Sterile ν , Extra Dim., Dark Energy

Leptogenesis: Matter-Antimatter Asymmetry

- More baryons than antibaryons in our Universe
 - Leptogenesis Scenario:
 1. Heavy Majorana Neutrinos Created and Decay
 $N \rightarrow H^- e^+$, $H^0 \bar{\nu}$ (L & CP VIOLATION)
Leads to antilepton (excess)-lepton Asymmetry
 2. Electroweak Phase Transition (250GeV) (Baryogenesis)
't Hooft Mechanism **B-L Conserved (B&L Violated)**
antilepton excess \rightarrow baryon (quark) excess by 1 in 10^9
- Is L Violated in Nature? (Neutrinoless $\beta\beta$ Decay)
Is there Leptonic CP Violation? (ν oscillations)
Indirect evidence for Leptogenesis (Best we can do.)

Leptonic CP Violation

$$P(\nu_\mu \rightarrow \nu_e) = P_I(\nu_\mu \rightarrow \nu_e) + P_{II}(\nu_\mu \rightarrow \nu_e) + P_{III}(\nu_\mu \rightarrow \nu_e)$$

+ matter + smaller terms

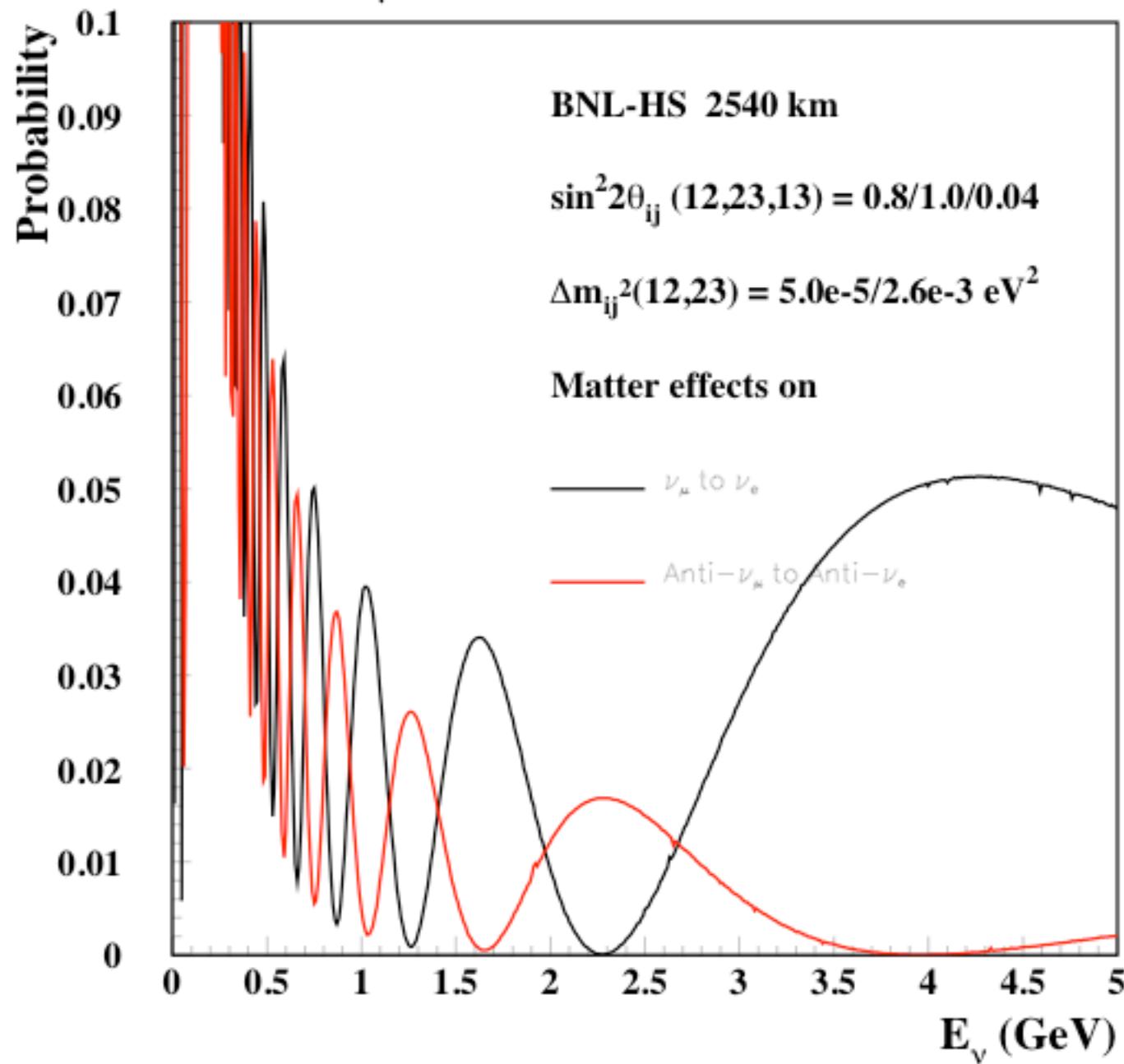
$$P_I(\nu_\mu \rightarrow \nu_e) = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E_\nu} \right)$$

$$\begin{aligned} P_{II}(\nu_\mu \rightarrow \nu_e) &= \frac{1}{2} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos \theta_{13} \\ &\quad \sin \left(\frac{\Delta m_{21}^2 L}{2E_\nu} \right) \times \left[\sin \delta \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E_\nu} \right) \right. \\ &\quad \left. + \cos \delta \sin \left(\frac{\Delta m_{31}^2 L}{4E_\nu} \right) \cos \left(\frac{\Delta m_{31}^2 L}{4E_\nu} \right) \right] \end{aligned}$$

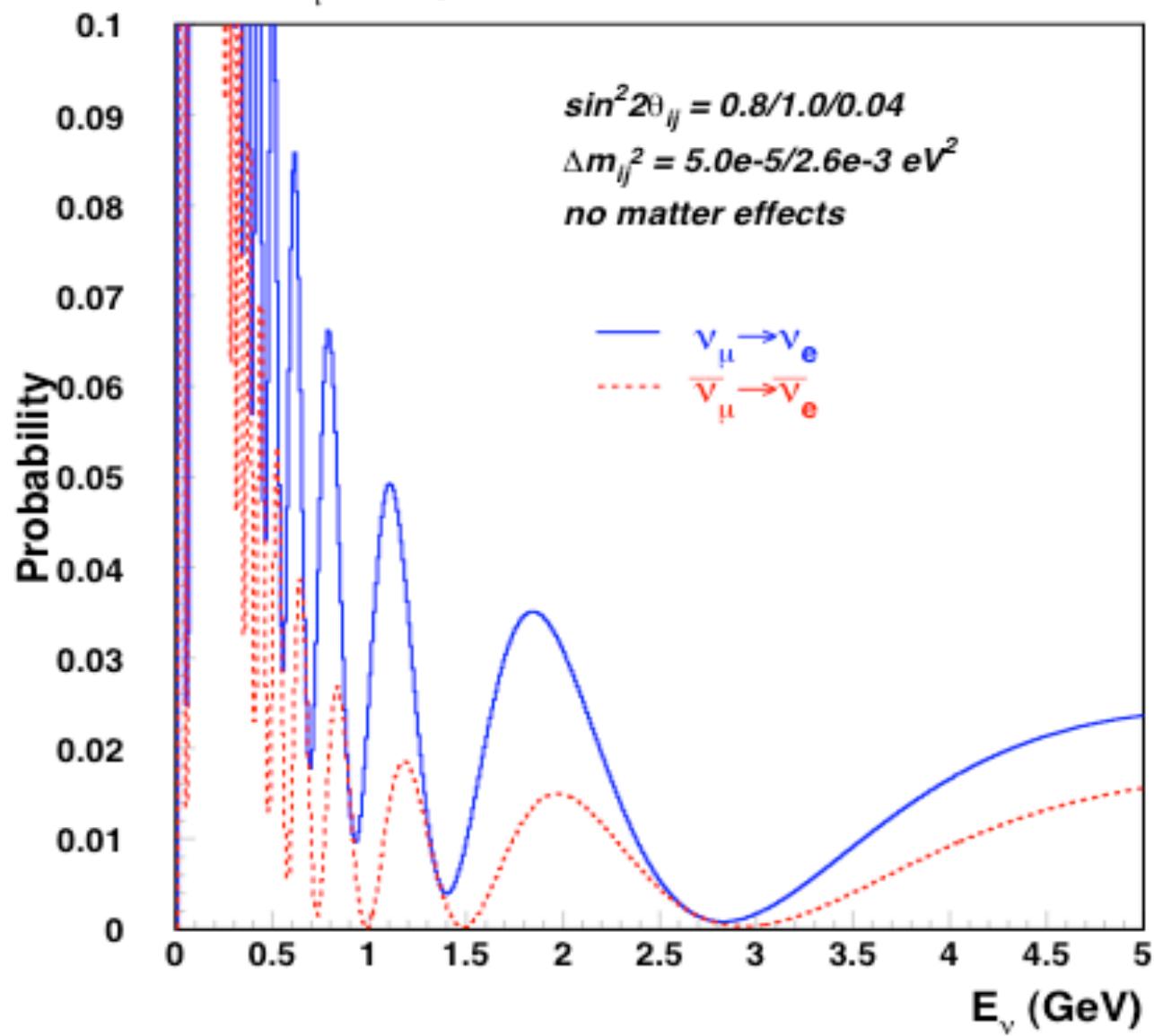
$$P_{III}(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{12} \cos^2 \theta_{13} \cos^2 \theta_{23} \sin^2 \left(\frac{\Delta m_{21}^2 L}{4E_\nu} \right)$$

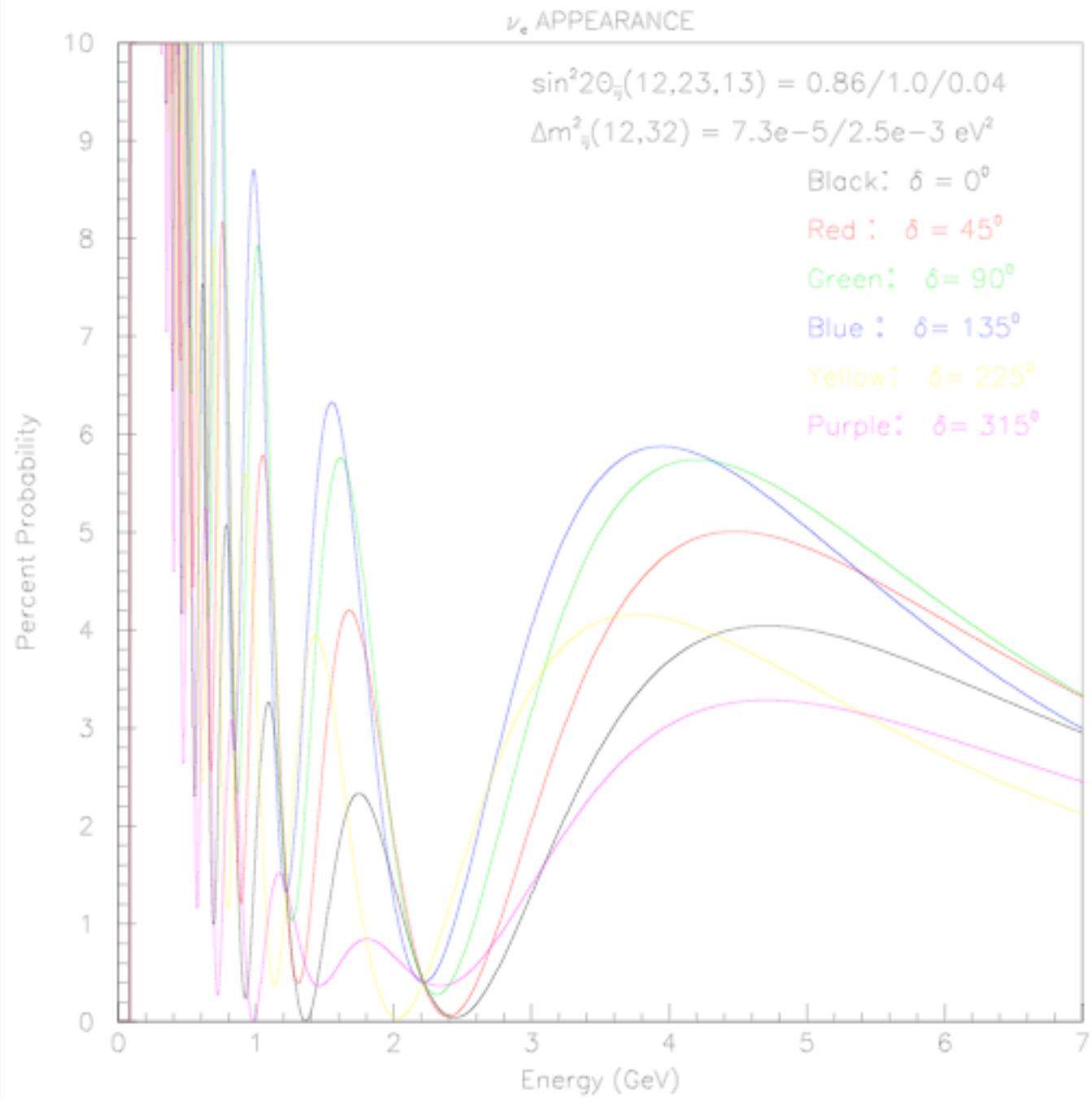
For antineutrinos, $\delta \rightarrow -\delta$ and opposite matter effect.

$P(\nu_\mu \rightarrow \nu_e)$ CP phase=45.



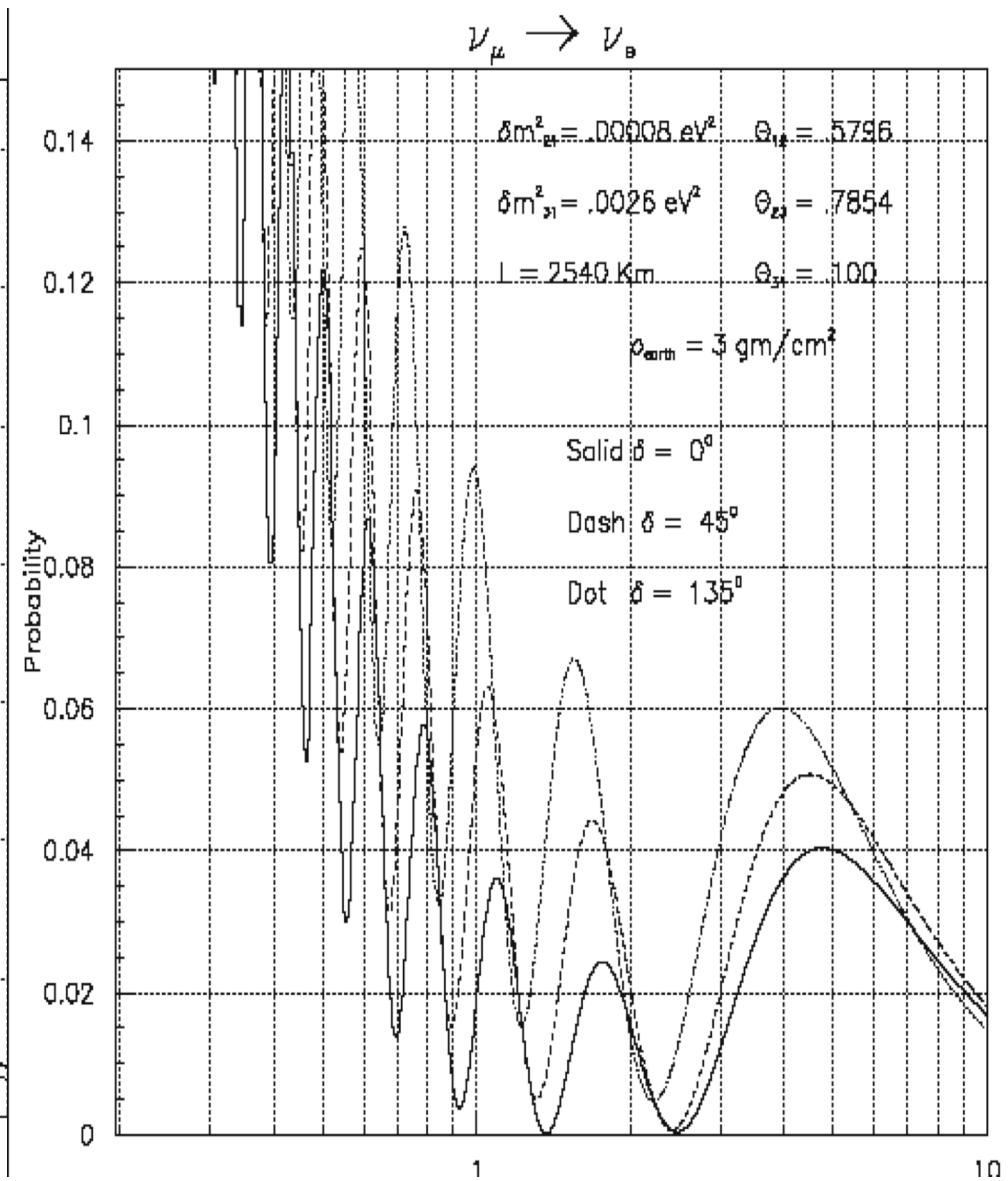
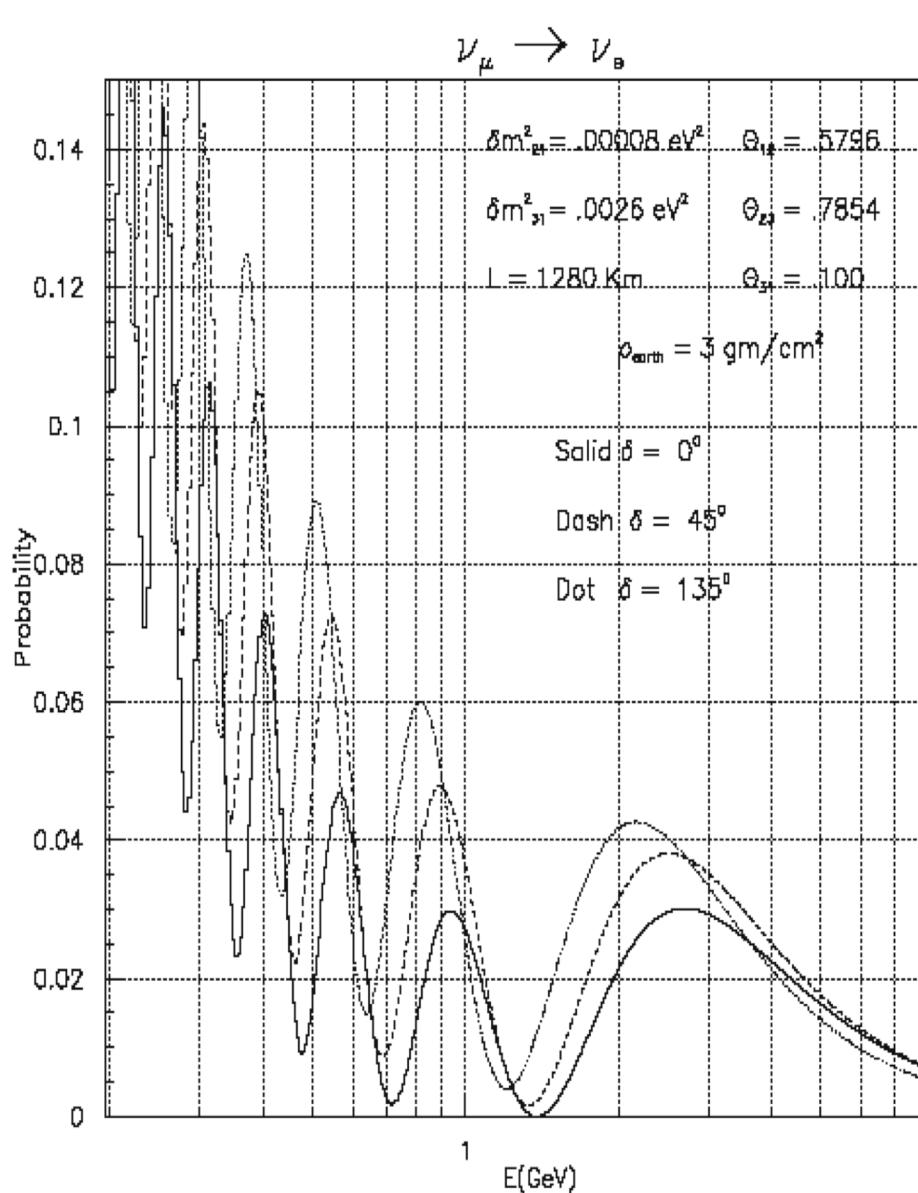
$P(\nu_\mu \rightarrow \nu_e)$ with 45° CP phase

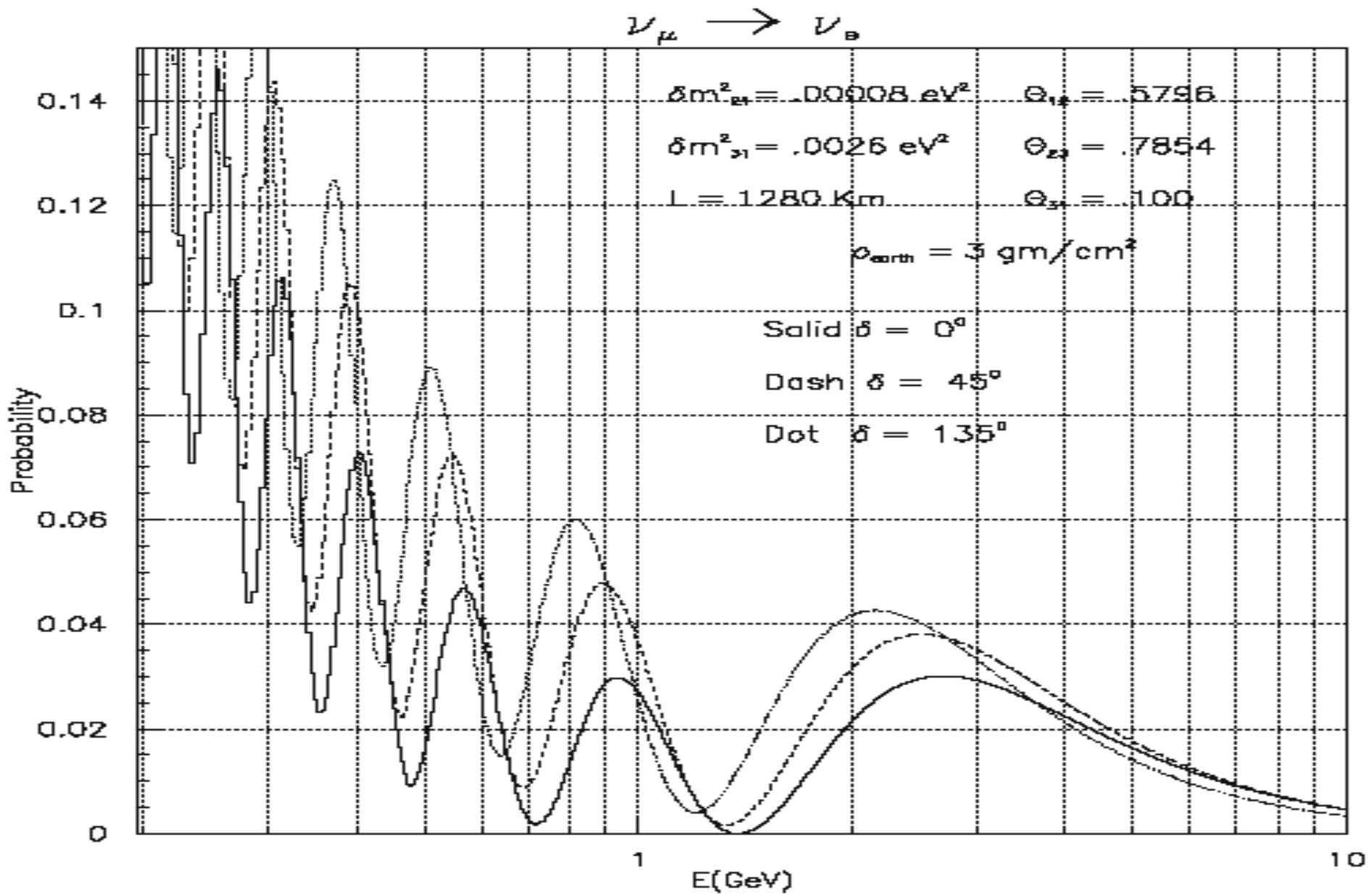




FNAL

BNL





CP Violation Asymmetry

$$A_{CP} \equiv \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \quad (3)$$

To leading order in Δm_{21}^2 ($\sin^2 2\theta_{13}$ is not too small):

$$A_{CP} \simeq \frac{\cos \theta_{23} \sin 2\theta_{12} \sin \delta}{\sin \theta_{23} \sin \theta_{13}} \left(\frac{\Delta m_{21}^2 L}{4E_\nu} \right) + \text{matter effects} \quad (4)$$

$$F.O.M. = \left(\frac{\delta A_{CP}}{A_{CP}} \right)^{-2} = \frac{A_{CP}^2 N}{1 - A_{CP}^2} \quad (5)$$

N is the total number of $\nu_\mu \rightarrow \nu_e + \bar{\nu}_\mu \rightarrow \bar{\nu}_e$ events. Since N falls (roughly) as $\sin^2 \theta_{13}$ and $A_{CP}^2 \sim 1/\sin^2 \theta_{13}$, to a first approximation the F.O.M. is independent of $\sin \theta_{13}$. Similarly, given E_ν the neutrino flux and consequently N falls as $1/L^2$ but that is canceled by L^2 in A_{CP}^2 .

CP Violation Insensitivities

- To a very good approx., our statistical ability to determine δ or A_{cp} is independent of $\sin^2 2\theta_{13}$ (down to 0.003) and the detector distance (for long distance).

iii) CP Violation Requirements

- Pick any reasonable θ_{13} (eg $\sin^2 2\theta_{13} = 0.04$)
- What does it take to measure δ to $\pm 15^\circ$ in about 5×10^7 sec?

Answer (Approx.): [500kton Water Cerenkov Detector](#)

Approx 20% Acceptance,
[125 kton LArgon 80% Acceptance](#)
or Hybrid combination

+ Traditional Horn Focused v WBB powered by
[1-2MW proton accelerator](#) (AGS Linac Upgrade)

or

Project X with 2MW 50GeV protons $\sim 0.5-1^\circ$
off-axis (don't need high energy ≥ 4 GeV neutrinos)
(Very well matched to 300kton H₂O Detector)

TRADITIONAL HORN FOCUSED NEUTRINOS

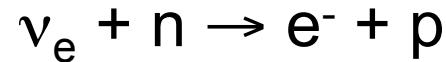
- Protons \Rightarrow target $\Rightarrow \pi^\pm$ (em focus down a long decay tunnel) (At Fermilab only 100-200m at $\sim 5^\circ$ incline)

- $\pi^+ \rightarrow \mu^+ + \nu_\mu$ (intense ν_μ beam results)

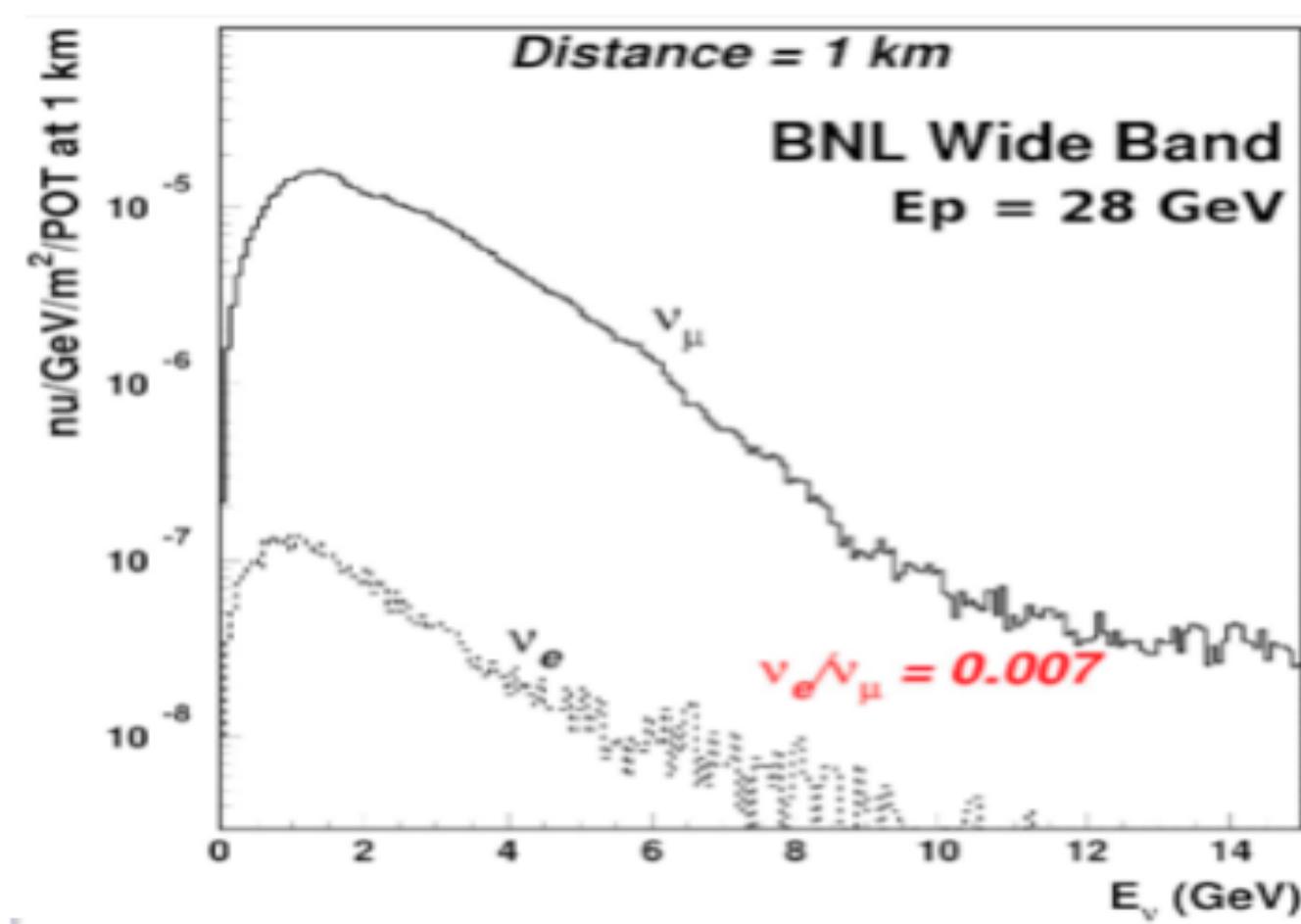
Very Efficient $\sim 1/3$ ν /proton

Off-Axis detector - lose high energy neutrinos

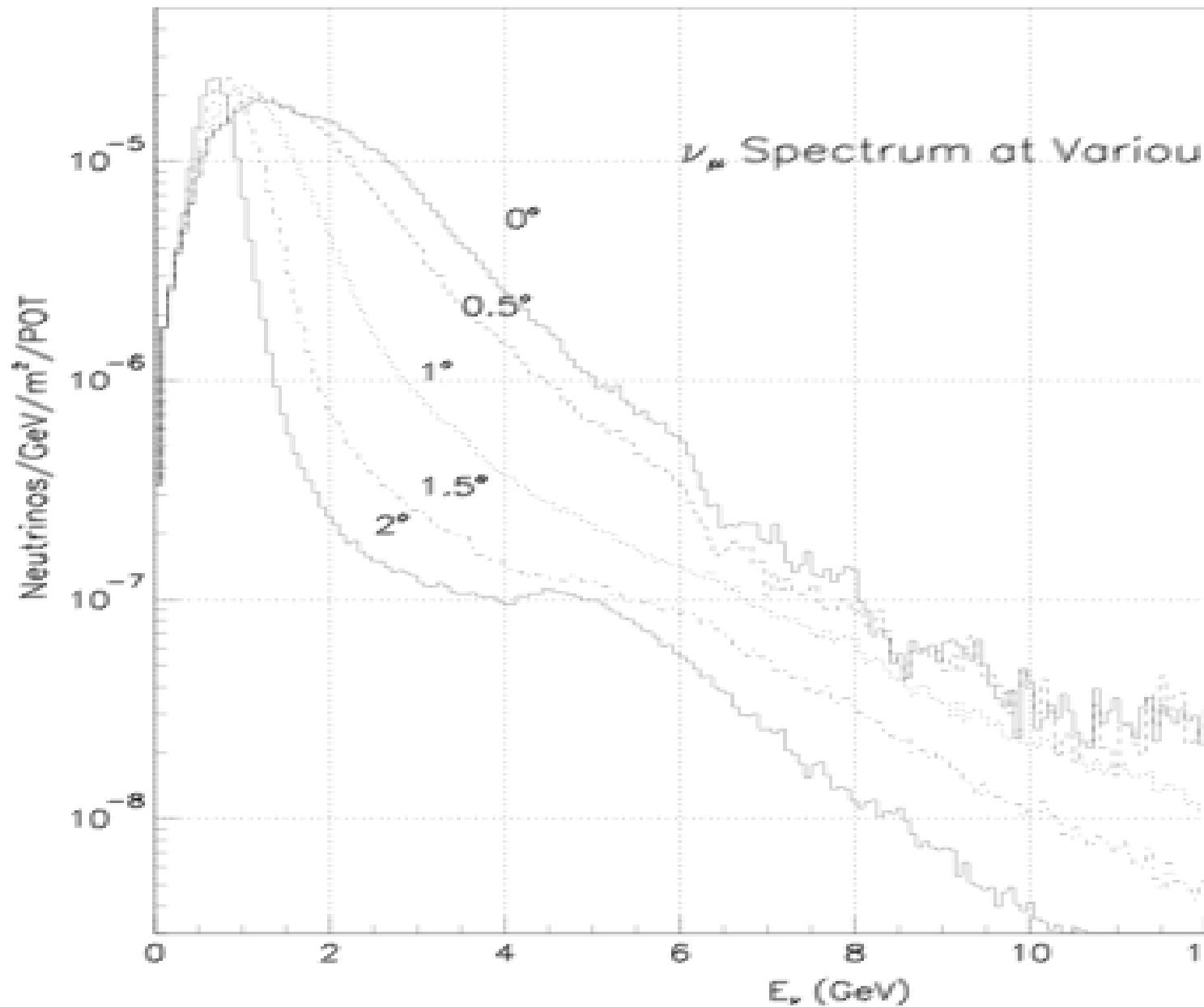
Detect $\nu_\mu + n \rightarrow \mu^- + p$ or if $\nu_\mu \rightarrow \nu_e$ oscillations



Horn Focused Neutrino Beam



ν_μ Spectrum at Various



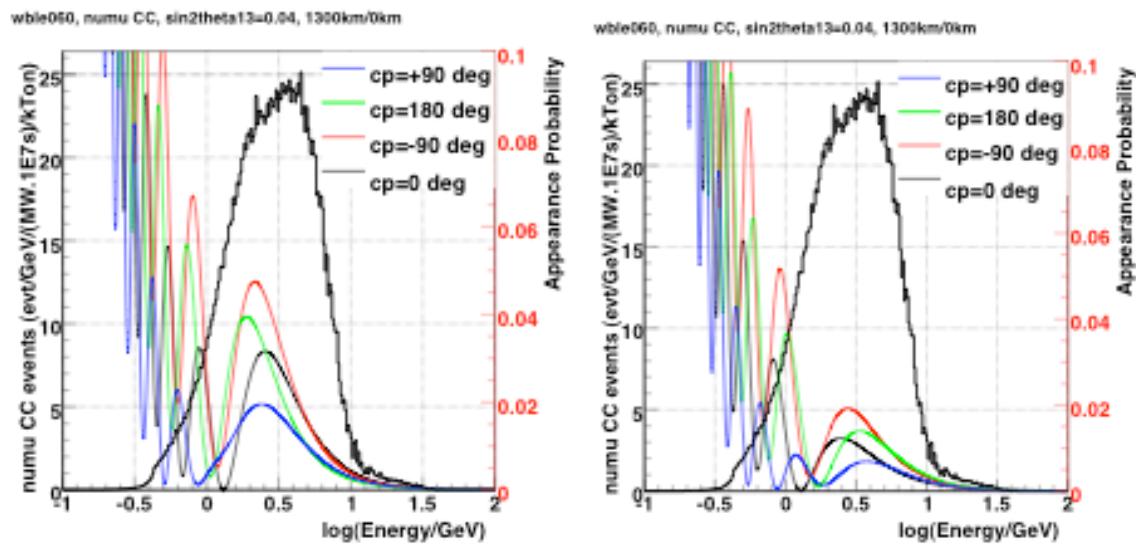
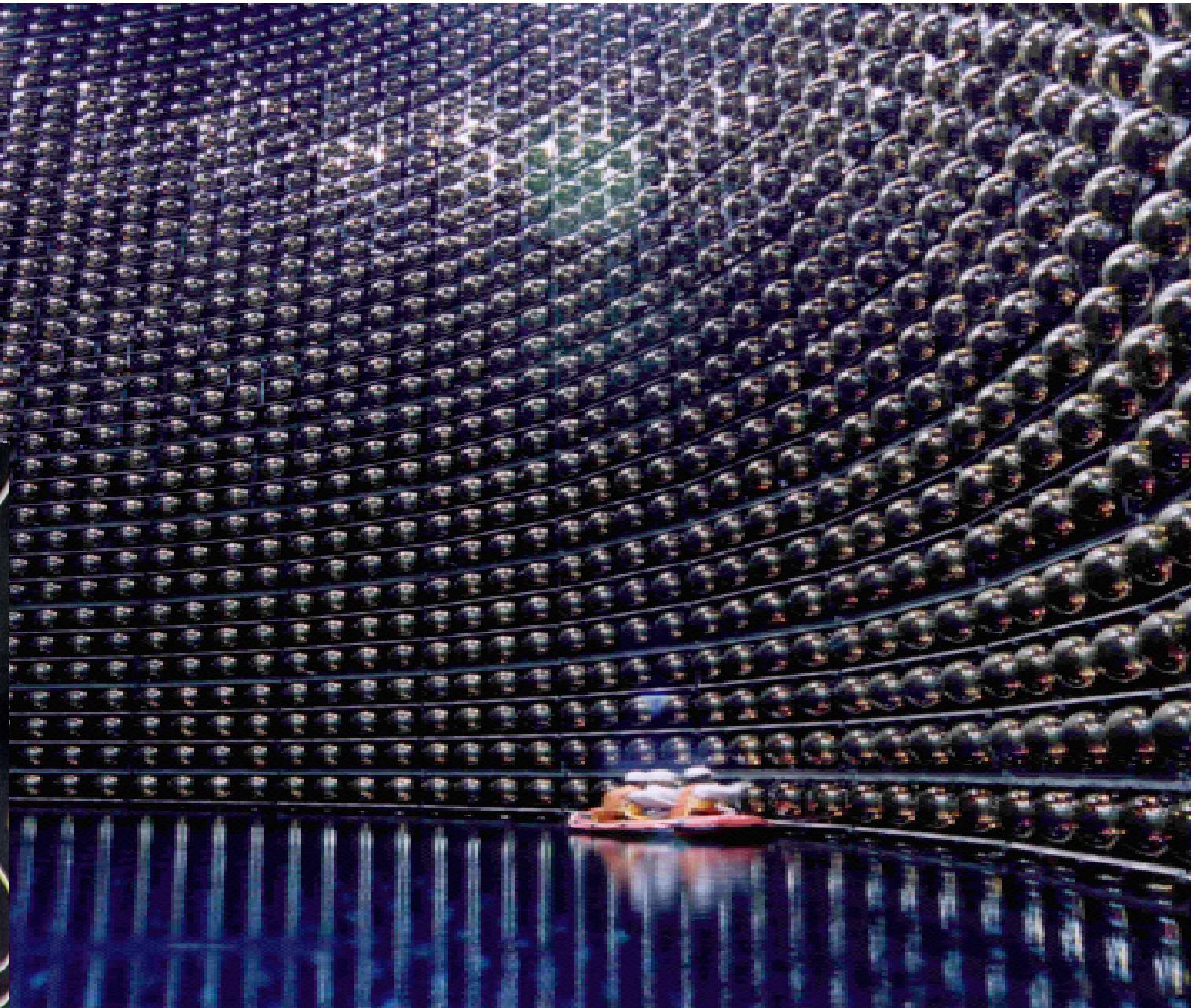
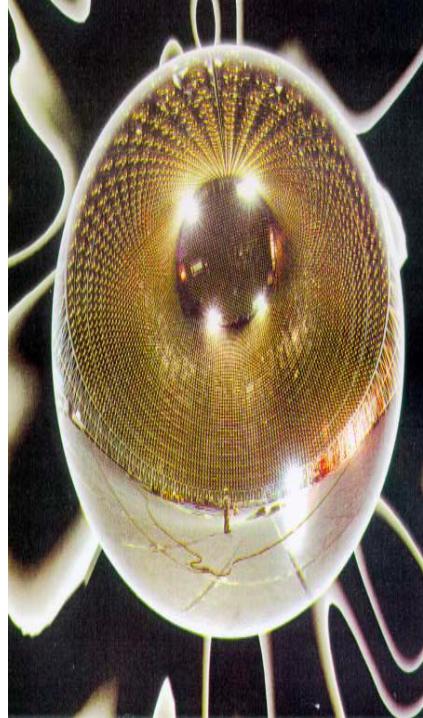


FIG. 3: (color) Spectrum of charged current ν_μ events using a new wide band beam from FNAL to a location at 1300 km. The spectrum is normalized per GeV per $MW \times 10^7 sec$ protons of 60 GeV. Overlayed is the probability of $\nu_\mu \rightarrow \nu_e$ conversion for $\sin^2 2\theta_{13} = 0.04$ with rest of the oscillation parameters as described in the text. The left plot is for regular mass ordering and right hand side is for reversed mass ordering. Figure includes no detector effects such as efficiencies, resolution, or backgrounds.

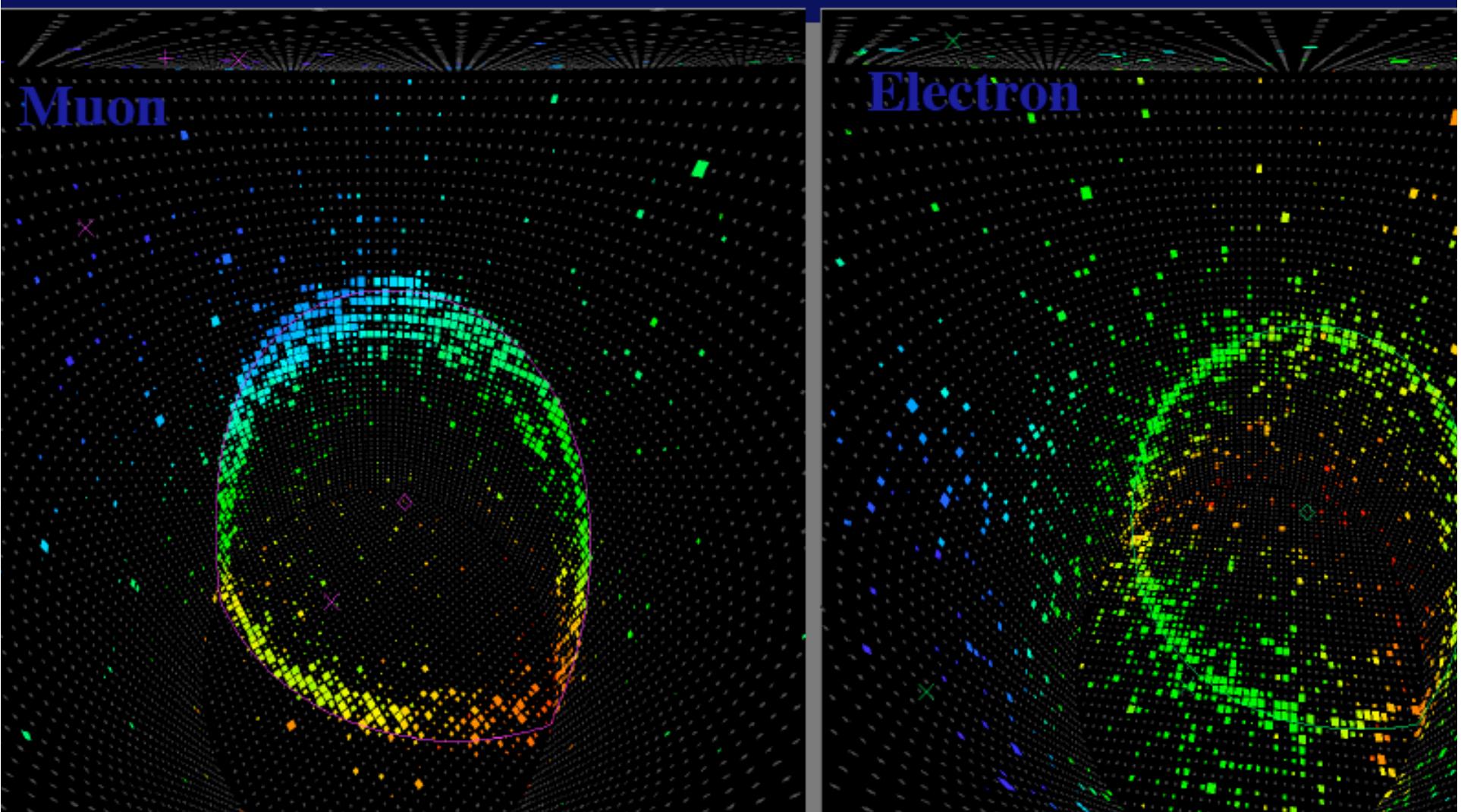
Requirements

- 300-500 kton H₂O (or equivalent)
- 1-2 MW proton beam (Superbeam)
- 3 ν + 3 $\bar{\nu}$ yrs running time
- Flagship of DUSEL
- Many Potential Revolutionary Discoveries (50yrs of Physics)

SUPER KAMIOKANDE



Particle Identification



Physics Program (Big Underground Detector)

i) Neutrino Physics (Osc., Astro., Cosmology)

Atmospheric $\nu_\mu \rightarrow \nu_\tau$ osc (precision)

Solar $\nu_e \rightarrow \nu_e, \nu_\mu, \nu_\tau$ (if needed)

***Supernova** $\bar{\nu}_e, \nu_\mu, \dots > 100,000$ events!

Relic Supernova ν (History of the Universe)

***Very Long Baseline (Star Attraction) (Needs FNAL)**

$\nu_\mu \rightarrow \nu_\mu$

$\nu_\mu \rightarrow \nu_e$

$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Oscillations

J

Supernova Neutrinos

- SN 1987A: 19 events observed by Kamiokande & IMB
 $\bar{\nu}_e p \rightarrow e^+ n$ **Great Discovery - Confirmed SN Models**
A SN in our galaxy (every ~ 40 yr) at typical 10kpc would lead to about 100,000 $\bar{\nu}_e p \rightarrow e^+ n$ events/300kton H₂O
Also, $\nu e \rightarrow \nu e$, ($\nu = \nu_e, \nu_\mu, \nu_\tau, \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$) ~ 1000 events
We would like to see $\nu_e + ^{40}\text{Ar} \rightarrow e^- + ^{40}\text{K}$ (initial burst)
 ~ 250 events/kton LArgon
Neutrino Spectrum \rightarrow SN Dynamics & Oscillations
Extremely Rich Discovery Possible
We must have as many detectors as possible online
Relic SN Neutrinos (10-40MeV) S/B/yr $\sim 10/10$

Goals: Measure all ν osc. parameters.

- $\Delta m^2_{32} = m^2_3 - m^2_2 = \pm 2.6(3) \times 10^{-3} \text{ eV}^2$ to $\pm 1\%$
- $\Delta m^2_{21} = m^2_2 - m^2_1 = 7.6(2) \times 10^{-5} \text{ eV}^2$ to $\pm 5\%$ in appearance
- $\sin^2 2\theta_{23} \approx 0.9 - 1.0$ to ± 0.01 (**Break Degeneracy**)
- $\sin^2 2\theta_{12} \approx 0.84 \pm 0.10$ to ± 0.03 (?)
- $\sin^2 2\theta_{13} \approx 0.15 \sim 0.003$
- Sign of Δm^2_{32}
- δ to $\pm 15^\circ$ (CP Violation)
- Sterile ν , Extra Dim, Dark Energy? ...

ν_μ Disappearance

Neutrino Running

- Total exposure: 2500 kT.MW.(10^7).sec
- 195000 CC evts/6yrs: 2MW-FNAL, 100kT-HS
- Use only clean single muon events.

Measurements

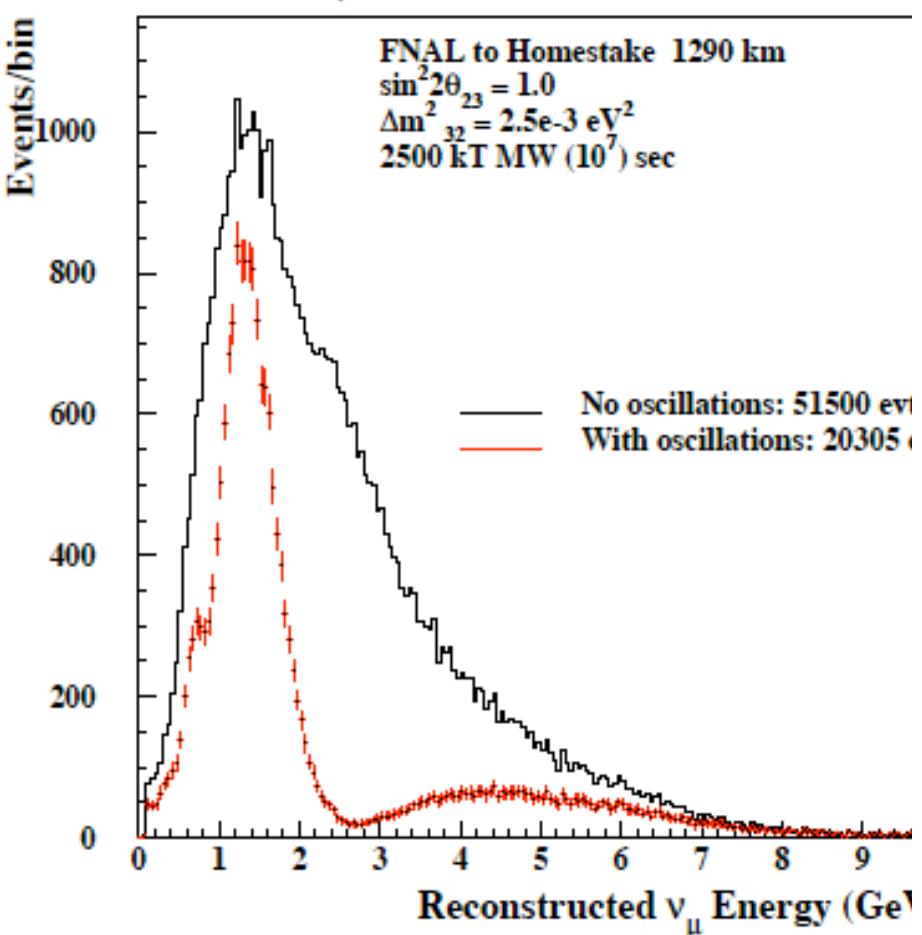
- 1% determination of Δm_{32}^2
- 1% determination of $\sin^2 2\theta_{23}$
- Most likely systematics limited.

$\bar{\nu}$ running

- Need twice the exposure for similar size data set.
- very precise CPT test possible.

Very easy to get this effect
Does not need extensive pattern recognition. Can enhance the second minimum by background subtraction

ν_μ disappearance



ν_e Appearance

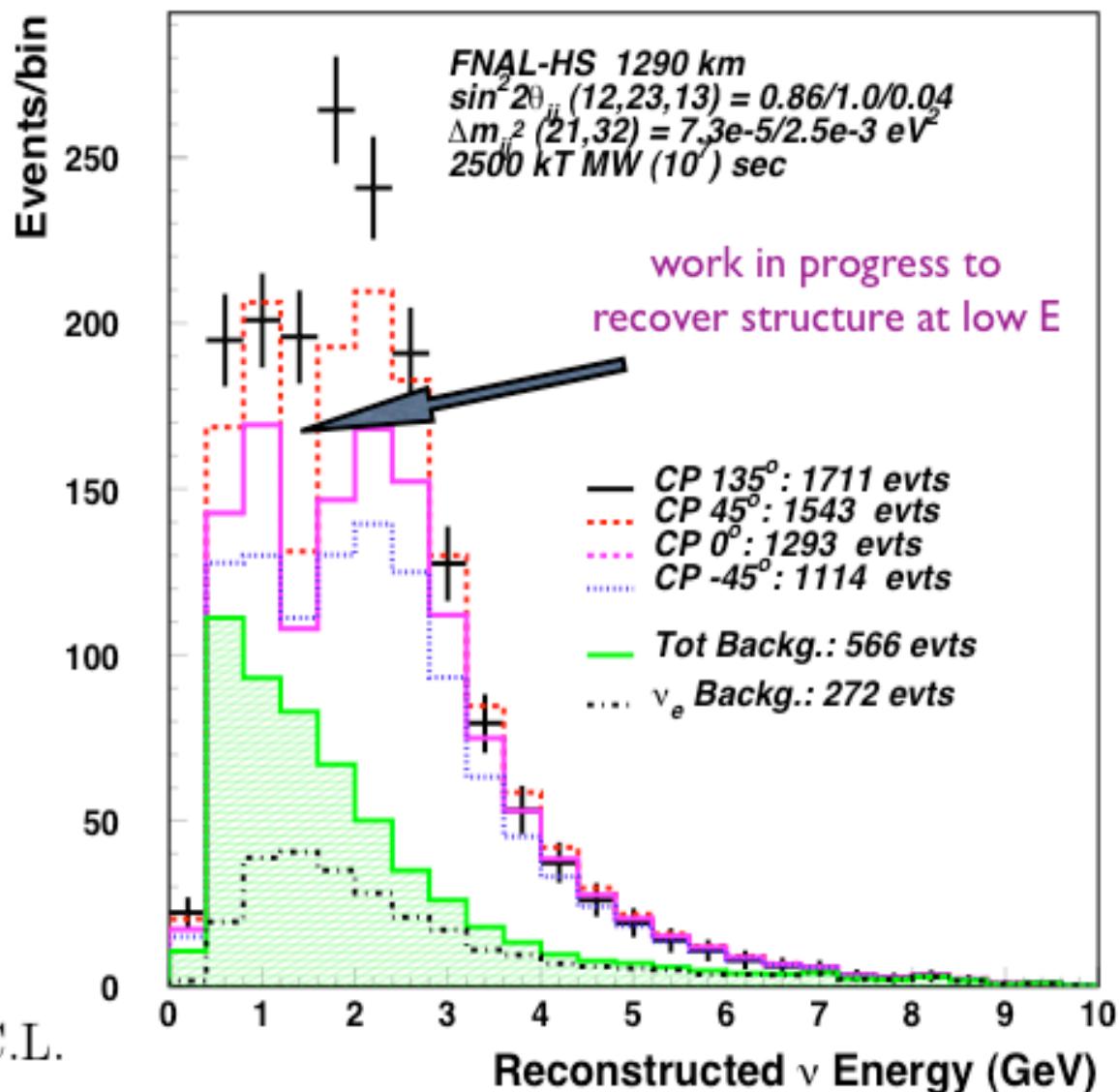
Backgrounds

- beam ν_e
- Neutral current events

ν running

- measure $\sin^2 2\theta_{13}$ and δ_{CP} .
- resolve mass hierarchy for $\sin^2 2\theta_{13} > 0.01$
- with $\bar{\nu}$ running
 $\sin^2 2\theta_{13} > 0.003$ at 90% C.L.

ν_e APPEARANCE



- For details see: Report of the US Long Baseline Neutrino Experiment Study

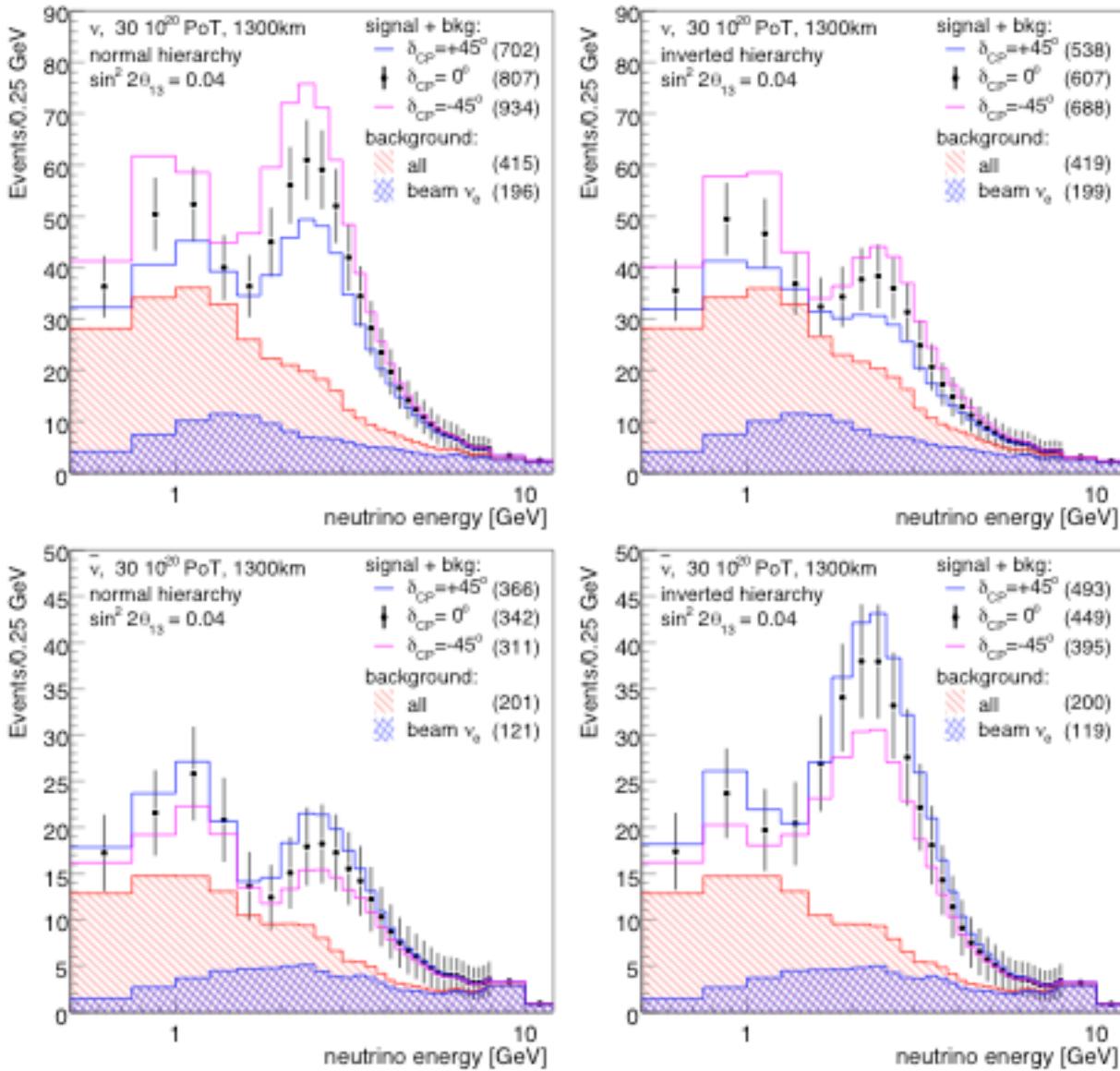


FIG. 9: Simulation of detected electron neutrino (top plots) and anti-neutrino (bottom plots) spectrum (left for normal hierarchy, right for reversed hierarchy) for 3 values of the CP parameter δ_{CP} , -45° , 0° , and $+45^\circ$, including background contamination. This simulation is for 300 kT of water Cherenkov detector with

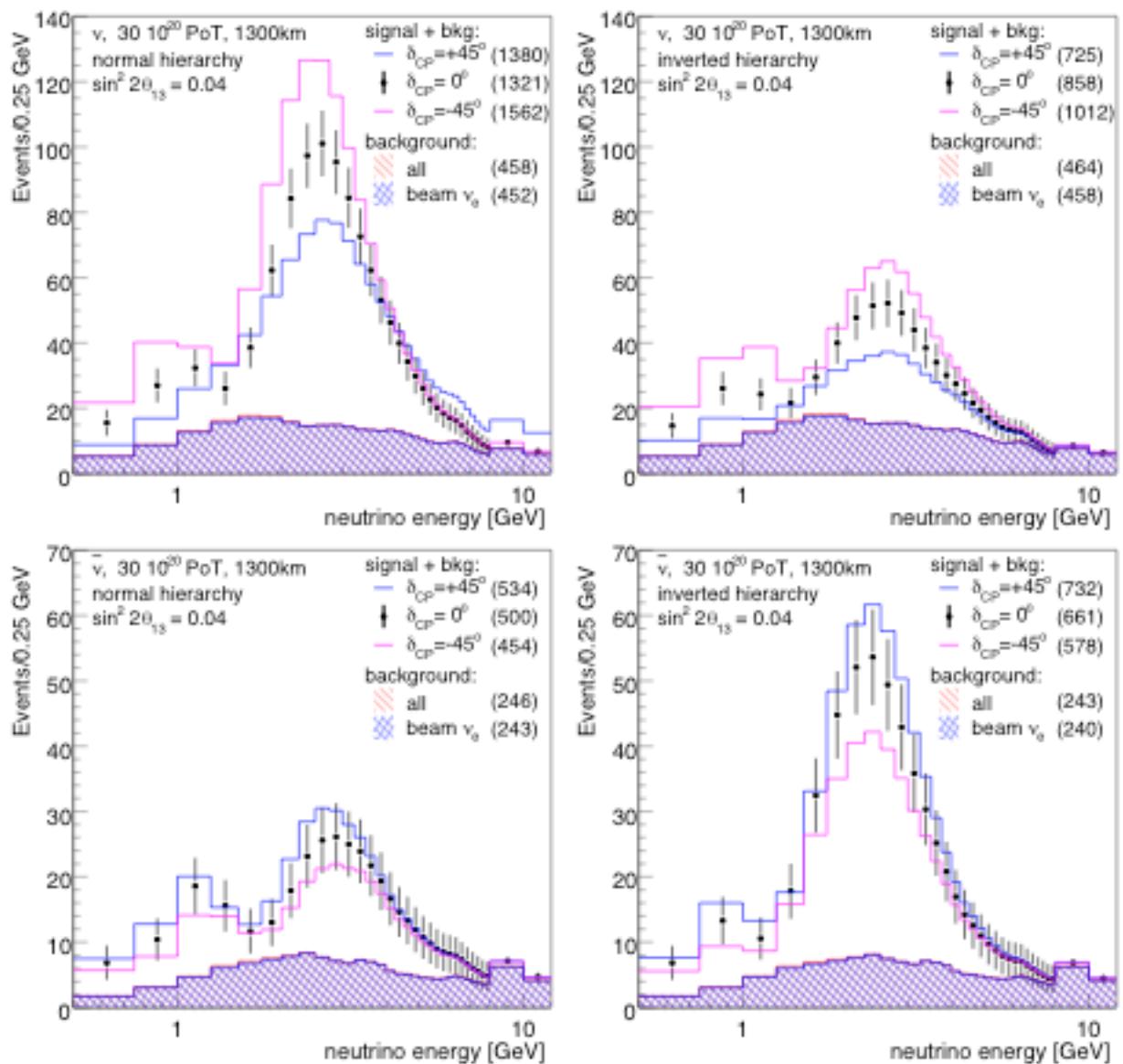
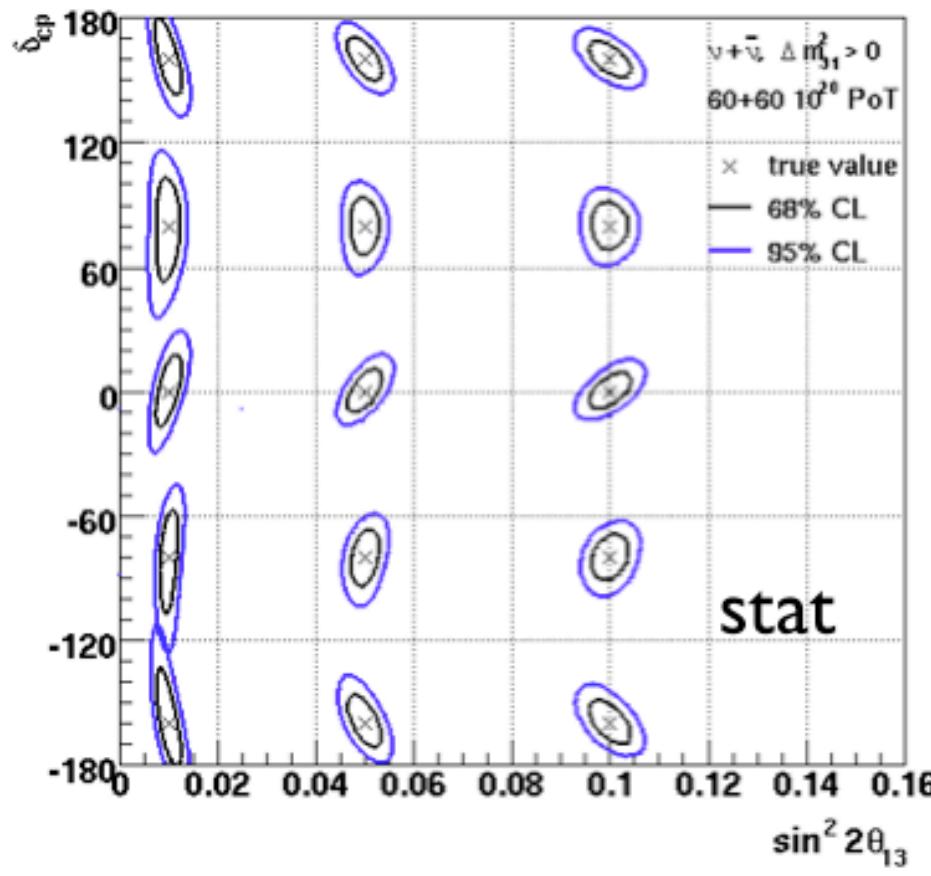


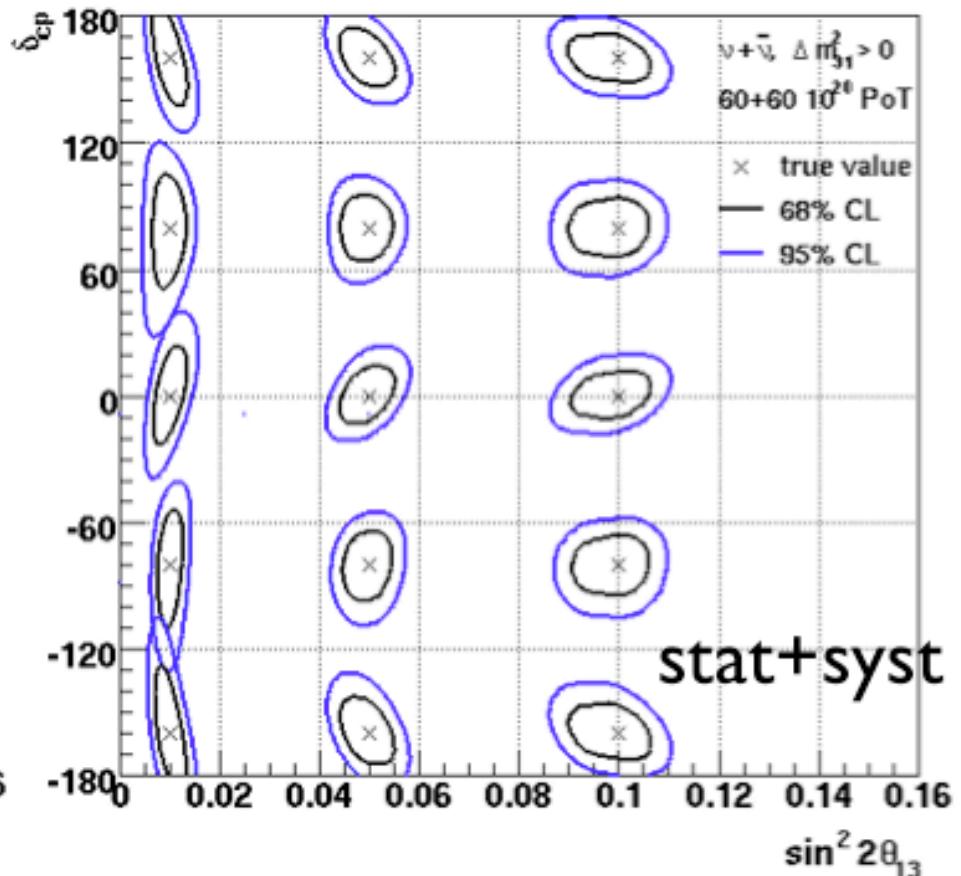
FIG. 18: Simulation of detected electron neutrino (top plots) and anti-neutrino (bottom plots) spectrum (left for normal hierarchy, right for reversed hierarchy) for 3 values of the CP parameter δ_{CP} , -45° , 0° , and $+45^\circ$, including background contamination. This simulation is for 100 kT of LAr detector (with the

CP Phase Insensitivity to θ_{13} Value

WCC 1300 km 300kT



(-95% CL -68% CL)



ii) **Proton Decay (Gauge Boson Mediated)**

$(X^{\pm 4/3}, Y^{\pm 1/3})$: $\tau(p \rightarrow e^+ \pi^0) \geq 10^{34} \text{yr}$ SuperK Goal

SuperK 22.5Kton H₂O Fiducial Vol.

Next Generation $\rightarrow 10^{35} \text{yr} \rightarrow > 300 \text{Kton H}_2\text{O}$

SUSY GUTS $\tau(p \rightarrow e^+ \pi^0) \approx 10^{35} (m_X/10^{16} \text{GeV})^4 \text{yr}$

Other decay modes $p \rightarrow K^+ \nu, \dots$

Egs. UNO Proposal 500Kton H₂O (22xSuperK)

Homestake 300Kton H₂O (Phase I) Modular

(Cost $\approx \$1 \text{M/kton}$)

Also Does: Magnetic Monopoles (GUT 10^{18}GeV)

(Catalyze Proton Decay $p + M \rightarrow e^+ + M$)

Neutron-Antineutron Osc. (10^9sec)

Virtual Black Hole Proton Decay...

(ν CP Violation & Proton Decay $\rightarrow 500 \text{kton H}_2\text{O}$)

6. Outlook

- Fermilab should (must) do $\mu \rightarrow e$ at 2×10^{-17}
- (Preparation for 10^{-18} - 10^{-19} and future muon physics)
- We can advance: ν CP Violation, θ_{13} , Hierarchy,...
- Atmospheric ν , Solar(?)
- 100,000 supernova ν events (if in our galaxy)!
- Observe relic supernova ν (universe history)!
- Exotic effects: sterile ν , extra dim. dark energy...
- Proton decay, $n - \bar{n}$ osc.,... magnetic monopoles
- Potential for major discoveries is great!
- Requires Big Detector: 500kton H_2O or equivalent
- 50 yrs of physics investment! National Program

Fermilab Activities

- What does Fermilab do after the LHC starts?
- (Great Hope - ILC e^+e^- Collider ($\mu^+\mu^-$ Collider?))

In the meantime? New Working Group Reports

Project X Option- 8GeV proton linac (ILC R&D?)

*8GeV fixed target program (eg. $\mu N \rightarrow e N \dots$) superb!
+ Main Injector, Tevatron \bar{p} , hyperons, kaons, $\nu \dots$

MI: 2MW at 50GeV provides nice neutrino beam for
FNAL-Homestake (Cost ?) Total Project $\leq \$1$ Billion

IT'S A BARGAIN!

Doable! Must Do!

(START AS SOON AS POSSIBLE!)

Should be main focus of Fermilab FT Program